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RADIOSTRONTIUM FALLOUT: PROJECT SUNSHINE

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OS-6 JB 4/29/94

W. F. LIBBY

JULY, 1956

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ATOMIC WEAPON REPORT

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LIST OF FIGURES

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LIST OF TABLES

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CONVERSION FACTORS

"Average Soil"	= 20 g Ca/ft^2 in top 2.5"
1 MPC Unit in any medium (1000 Sunshine Units)	= 1 μc Sr^{90}/kg Ca = 2,200 dpm Sr^{90}/g Ca
1 megaton fission distributed uniformly over entire earth	= 0.0009 MPC Unit = 0.5 mc Sr^{90}/mi^2

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RADIOSTRONTIUM FALLOUT: PROJECT SUNSHINE

By W. F. Libby [redacted]

July, 1956

ABSTRACT

Analyses of soils, gummed paper fallout samples, rain samples, air filter samples, animal bodies, milk and cheese, and human bodies have been used to deduce a mechanism for the dissemination of Sr^{90} over the world's surface and into the biosphere. Megaton weapons may deposit a large fraction of their radioactive products in the stratosphere. For this fraction a world-wide dissemination of ultrafinely divided particulate matter in the stratosphere occurs, accompanied by a slow leakage through the tropopause into the troposphere from which rapid deposition occurs. The average storage time in the stratosphere appears to be about ten years with an uncertainty of about plus or minus five years. The total Sr^{90} put in the stratosphere to date amounts to some 12 millicuries (mc) of Sr^{90}/mi^2, if the activity were spread uniformly over the earth's surface. As of the present, the total relatively uniform deposition appears to be about 2.8 mc/mi^2, from the megaton weapons with an additional 1.5 mc/mi^2 in the latitudes 0 to 50°N from kiloton shots and the part of the megaton shots remaining in the troposphere. In the United States, the average total deposit appears to be higher at about 13 mc of Sr^{90}/mi^2, the increase being due to the Nevada tests.

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The stratospheric fallout seems to be relatively uniform over the entire surface of the earth, with some tendency to peak at equatorial

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latitudes, and some tendency to concentrate in regions of high rainfall. It appears that the mechanism involves a carrying down by rain or snow of the radiostrontium containing particles which manage to traverse the tropopause and enter the troposphere, although there is undoubtedly some direct deposition from the tropospheric air.

After deposition, the Sr^{90} enters the soil and is assimilated by the plants, because of its similarity to Ca. In addition, plants gain a considerable fraction of the precipitated radiostrontium by assimilation from the surface of the leaves. Sr^{90}, being chemically similar to Ca, is found largely in the animal skeleton. It constitutes a somatic hazard in that an average skeletal content of 10 microcuries (μc) in adults may be sufficient to produce bone tumors statistically observable in a large population. The small weights of Sr involved in the radiostrontium being considered, and the similarity of the element to Ca, justifies the assumption that its distribution in the body will follow that of Ca. The procedure has been developed, therefore, of quoting all radiostrontium assays in terms of the Sunshine Unit, which is equivalent numerically to 2.2 disintegrations/min of Sr^{90}/g of Ca, or 1/1000 of the maximum permissible concentration of 1 μc per standard man, or 0.001 MPC.

At the end of 1955, the average soil in the latitudes 0° to $50^{\circ}N$ is expected to show an assay of about 5 Sunshine Units (11 dpm/g Ca), while about 3.5 is expected elsewhere, the average soil being taken to contain 20 g of Ca/ft^2 in the top 2.5 inches in forms available for plant assimilation. Human bones were generally found to contain

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somewhat less than 1 Sunshine Unit, other people showing much lower contents, presumably due to the cessation of growth. The ratio of Sr^{90} to Ca in the bones of grazing animals, such as cattle and sheep, ran higher in many instances, rising to 20 or 30 times those in humans, presumably due to local conditions of low Ca content of the soil and the fact that these animals eat grass and thus assimilate the fallout directly. Milk products showed assays of 1 to 5 Sunshine Units, about 1/5 of that of the cows and their feed.

With an average residence time of 10 years (half-life of 7 years), one would expect the stratospheric mixing and spreading over the world would be essentially complete. Half of the total radiostrontium introduced into the stratosphere in the Castle Test (1954) series, for example, will have been deposited some 7 years later in 1961; 3/4 of it 14 years later in 1968, etc. Considering the rate of radioactive decay of Sr, whose half-life is 28 years (or an average life of 40 years), the total Sr^{90} content in the average soil from the presently produced Sr^{90} is expected to reach a maximum of about 12 Sunshine Units or 7 mc/mi^2 in about 1970. Thereafter, it will decrease about 50 percent every 28 years.

It is to be noted that radiostrontium constitutes comparatively little genetic hazard because it is located largely in the skeletal structure.

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I. EXPERIMENTAL MEASUREMENTS

Sr^{90} is of particular importance among the fission products because of chemical and physical characteristics which result in comparatively high retention in the skeleton. These are: chemical similarity to Ca, an element essential to both plants and animals; an average life of about 40 years, and a low rate of elimination from the skeleton. On the basis of studies of the comparative effects of Sr^{90} and Ra^{226} in experimental animals, and of the effects of Ra in humans, the generally accepted maximum permissible body burden (skeletal content) of Sr^{90} in adult humans is 1 microcurie (μc). Since the body of the average adult contains about 1,000 g of Ca, this is equivalent to saying that the maximum permissible average concentration of Sr^{90} in the adult skeleton is 1 μc per 1,000 g of Ca. For purposes of this discussion, this ratio of Sr^{90} to Ca, in whatever medium it may occur, is designated an MPC Unit. One MPC Unit of Sr^{90} in the human body is considered to be safe -- a significant risk occurring only at much higher dosages.[1/] The majority of analyses for Sr^{90} encountered in this work were of the order of a few thousandths of 1 MPC Unit. For purposes of orientation it is helpful to remember that 0.001 MPC corresponds to 1/1000 μc of Sr^{90}/kg of Ca, or 2.2. dpm of Sr^{90}/g of Ca. This concentration is called the Sunshine Unit.

Throughout this paper, concentrations of Sr^{90} are given either in Sunshine Units or in MPC Units, remembering that 1 Sunshine Unit = 0.001 MPC Units = 1 milli MPC Unit.

The small weights of Sr^{90} involved in both the radiostrontium and normal Sr being considered, and the similarities of ~~the element~~

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to Ca justify the assumption that its distribution in the body will follow that of Ca in a general way.

Two megatons of fission at the average fission yield of 3.7% will produce 1 millicurie (mc) of Sr^{90}/mi^2, if the fission products are uniformly distributed over the earth's surface. If this amount of radioactivity were mixed with the available Ca in the soil, an average of about $20g/ft^2$ in the top 2.5 inches of soil, the specific radioactivity produced would be 1.8 Sunshine Units (0.018 MPC units). It is observed that most of the Sr^{90} fallout is concentrated in the top 1 or 2 inches of soil. For example, in Tables 1 and 2, which show the Sr^{90} burden in the fall of 1953 in 12 farms in the Wisconsin-Illinois area in the alfalfa and the milk of the cows fed thereon, we note that the top inch of soil contains about 56% and the next 5 inches contain the remaining 44% of the total Sr^{90}. Recently some evidence has been discovered that the radiostrontium finds its way to greater depths.[4] In Table 2 data are given for Iowa soil collected in 1937 which, as expected, shows no Sr^{90}. The average available Ca content of the domestic soils was 8 ± 1 g Ca/ft^2/inch, the average fraction of total Ca exchangeable was $68 \pm 3\%$, and the average Sr^{90} content was 4.7 ± 0.4 mc/mi^2 for an average of 8.55 Sunshine Units on the 2.5" average basis.

As might be expected because of the similarity of the Sr chemistry to that of Ca, milk and cheese show radiostrontium without exception. Figures 1a, b, c, and d show the data for both foreign and domestic samples.

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TABLE 1

BIOSPHERE Sr^{90} ASSAY 2/, 7/

WISCONSIN MILK SHED -- PRE-CASTLE, OCT. 1953

FARM*	SOIL (S.U.) 0"-1"	SOIL (S.U.) 1"-6"	TOTAL Sr^{90} (mc/mi^2)	ALFALFA (S.U.)	MILK (S.U.)
Grabow, Wisc.	26.2	6.7	4.5	12.8	1.7
Oliver Swain,"	7.4	2.2	3.1	5.3	1.3
Swanson, Ill.	15.8	2.5	9.2	7.1	1.2
Holcomb, Wisc.	8.7	1.8	5.1	8.3	1.6
Lewke, Wisc.	10.2	2.9	3.5	20.9	2.3
Premo, Wisc.	13.1	2.5	3.8	4.1	0.7
Kurpeski, Ill.	16.3	5.6	4.0	7.4	1.3
Austin, Ill.	22.4	4.7	4.7	5.0	1.8
McKee, Ill.	8.1	0.9	6.3	14.8	1.4
Blomberg, Ill.	1.7	<0.3	(4)	9.5	1.2
Van Winkle, Ill.	13.8	7.9	3.8	5.0	--
Carver, Ill.	42.1	5.6	3.3	2.3	--
Average (S.U.)	16.8	3.9		8.9	1.4
Average Sr^{90} (mc/mi^2)	2.6	2.1	4.7 ± 0.4		
Total Sr^{90}		4.7 ± 0.4			

*Samples collected by Dr. Lyle T. Alexander, Chief, Soil Survey Laboratory, Plant Industry Station, Beltsville, Maryland.

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TABLE 2

1953 DOMESTIC PRE-CASTLE SOIL SAMPLES

Location	Lab Number	Date Sample Taken	Area of Sample (ft^2)	Depth of Sample (inches)	Ca Extracted (N NH_4Ac reflux) (Grams)	Weight Sample Extracted (Pounds)	Exchange-able Ca Analytical Methods (me/100g)	Total Weight Sample Taken (Pounds)	Calc. Exch. Ca in Sample (Grams)	Calc. Calcium (g/ft^2)	Percent Ca Extracted (Column 10)	S.U.	Total Sr^{90} (mc/mi^2)	
Rock Co., Wisc. Site #1 Knox fine sandy loam Grabow Farm	531665	9/28/53	1.5	0-1	3.2	10.0	4.8	11.0	4.8	3.2	72.7	26.2	2.3	
Rock Co., Wisc. Site #1 Knox fine sandy loam	531665	9/28/53	1.5	0-1	1.0	10	4.8	11.0	4.8	3.2	(6N HCl after NH_4Ac extract)	24.6		4.5
Do	531666	9/28/53	0.3	1-6	3.0	10	3.5	11.0	3.5	11.7	93.8	6.7	2.2	
Rock Co., Wisc., Swain Farm, Site #2, Knox fsl.	531667	9/28/53	1.4	0-1	10.8	9.5	8.5	10.5	8.1	5.8	147	7.4	1.2	3.1
Do	531668	9/29/53	0.3	1-6	7.4	9.5	9.8	10.5	9.3	31.0	88.1	2.2	1.9	
Winnebago Co., Illinois Swanson Farm, Site #3 Carrington lib. sil	531669	9/29/53	1.2	0-2	9.5	6.0	13.9	7.0	8.8	7.3	125	15.8	3.2	5.9
Do	531670	9/29/53	0.24	1-6	10.0	6.5	13.5	7.5	9.2	38.3	125	2.5	2.7	
Rock Co., Wisc., Holcomb Farm Site #4 Carrington sil	531671	9/29/53	1.33	0-1	9.4	6.5	14.9	7.5	10.1	7.6	107	8.7	1.8	3.4
Do	531672	9/29/53	0.36	1-6	11.6	8	14.3	9.0	11.7	32.5	111	1.8	1.6	
Dave Co., Wisc., Lewke Farm, Miami sil, Site #4	531673	9/30/53	1.2	0-1	5.7	7	7.7	8.0	5.6	4.7	116	10.2	1.3	3.5
Do	531674	9/30/53	0.28	0-6	7.0	8.5	8.8	9.5	7.6	27.1	103	2.9	2.2	

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TABLE 2 (Cont'd)

Columbia Co., Wisc., Premo Farm, Miami sil, Site #6	531675	9/30/53	1.2	0-1	5.0	7.5	10.2	8.5	7.9	6.6	72.4	13.1	2.4	
Do	531676	9/30/53	1.2	0-1	2.0	7.5	10.2	8.5	7.9	6.6		12.5		3.8
Do	531676	9/30/53	0.30	1-6	8.2	9.0	6.7	10.0	6.1	20.3	149	2.5	1.4	
McHenry Co., Illinois Miami sil, Kurpeski Farm, Site #7	531677	9/30/53	1.16	0-1	5.0	7.0	6.4	8.0	4.6	4.0	122	16.3	1.8	4.0
Do	531678	9/30/53	0.30	1-6	5.0	9.0	4.7	10.0	4.3	14.3	132	5.6	2.2	
McHenry Co., Illinois Miami sil, Austin Farm, Site #8	531679	10/1/53	1.3	0-1	4.2	8.0	6.8	9.0	5.6	4.3	85.7	22.4	2.7	4.7
Do	531680	10/1/53	0.31	1-6	3.9	9.5	5.1	10.5	4.9	15.8	88.6	4.7	2.0	
McHenry Co., Illinois McKee Bros. Farm, Site #9, Drummer rich	531681	10/1/53	1.14	0-1	16.0	27.0	25.9	8.0	18.8	16.5	97.0	8.1	3.7	
Do	531681	10/1/53	1.14	0-1	10.0	7.0	25.9	8.0	18.8	16.5	(6N HCl after NH_4Ac extract)	4.0		6.3
Do	531682	10/1/53	0.24	1-6	23.5	9.0	27.4	10.0	24.9	103.8	105	0.9	2.6	
McHenry Co., Illinois Blomberg Farm, Site #10, Drummer rich	531683	10/1/53	.85	0-1	8.0	5.0	25.6	6.0	13.9	16.4	69.0	1.65	(0.8)	
Do	531683	10/1/53	.85	0-1	5.0	5.0	25.6	6.0	13.9	16.4	(6N HCl extraction following NH_4Ac)	4.4	2.0	
Do	531684	10/1/53	.22	1-6	17.5	8.0	25.4	9.0	20.8	94.5	95.1	0.3		

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TABLE 2 (Cont'd)

Will Co., Illinois Van Winkle Farm, Plainfield Sand, Site #11	531685	10/2/53	1.23	0-1	3.1	9.0	3.5	10.0	3.2	2.6	107	13.8	1.0	3.8
Do	531686	10/2/53	0.26	1-6	3.8	10.5	3.2	11.5	3.3	12.7	127	7.9	2.8	
Will Co., Illinois Carver Farm, Site #12 Plainfield Sand	531687	10/2/53	1.38	0-1	2.1	9.0	2.8	10	2.5	1.8	91.3	42.1	2.1	3.3
Do	531688	10/2/53	.35	1-6	2.2	11.0	2.4	12	2.6	7.5	91.7	5.6	1.2	
Utah, College Pasture	531689	10/53	1.45	0-1	11.2	7.5	28.0	7.5	19.1	13.2	58.6	1.38	0.51	0.98
Utah, College Pasture	531690	10/53	0.265	1-6	13.2	8.5	28.8	8.5	22.2	83.4	59.4	0.20	0.47	

Average Ca Content (exchangeable) = 8.0 $\pm$ 1 gms Ca/ft^2/in. = 8.6 $\pm$ 1 mg Ca/cm^2/in.

Average Fraction of Total Ca Exchangeable = 68% $\pm$ 3 (Assuming 6N HCl to extract all Ca.)

$$\frac{Sr^{90} \text{ Concentration } 1\text{-}6"}{Sr^{90} \text{ Concentration } 0\text{-}1"} = 0.23 \pm .027$$

Effective depth at top 1" concentration = 2.15" = 19 mg Ca/cm^2 = 18 g Ca/ft^2

Pre-atomic Samples:

Iowa, Carrington loam	C-2916	1937	0-3"	0 $\pm$ 0.05 Sunshine Units
Iowa, Carrington loam	C-2917	1937	3-13"	0 $\pm$ 0.05 Sunshine Units

Samples collected, analyzed except for Sr^{90} by Dr. L. T. Alexander, Beltsville, Maryland, U. S. Dept. of Agriculture.

All radiostrontium measurements made in Chicago Sunshine Laboratory, Refs. 2, 5, 6, 7 and 8.

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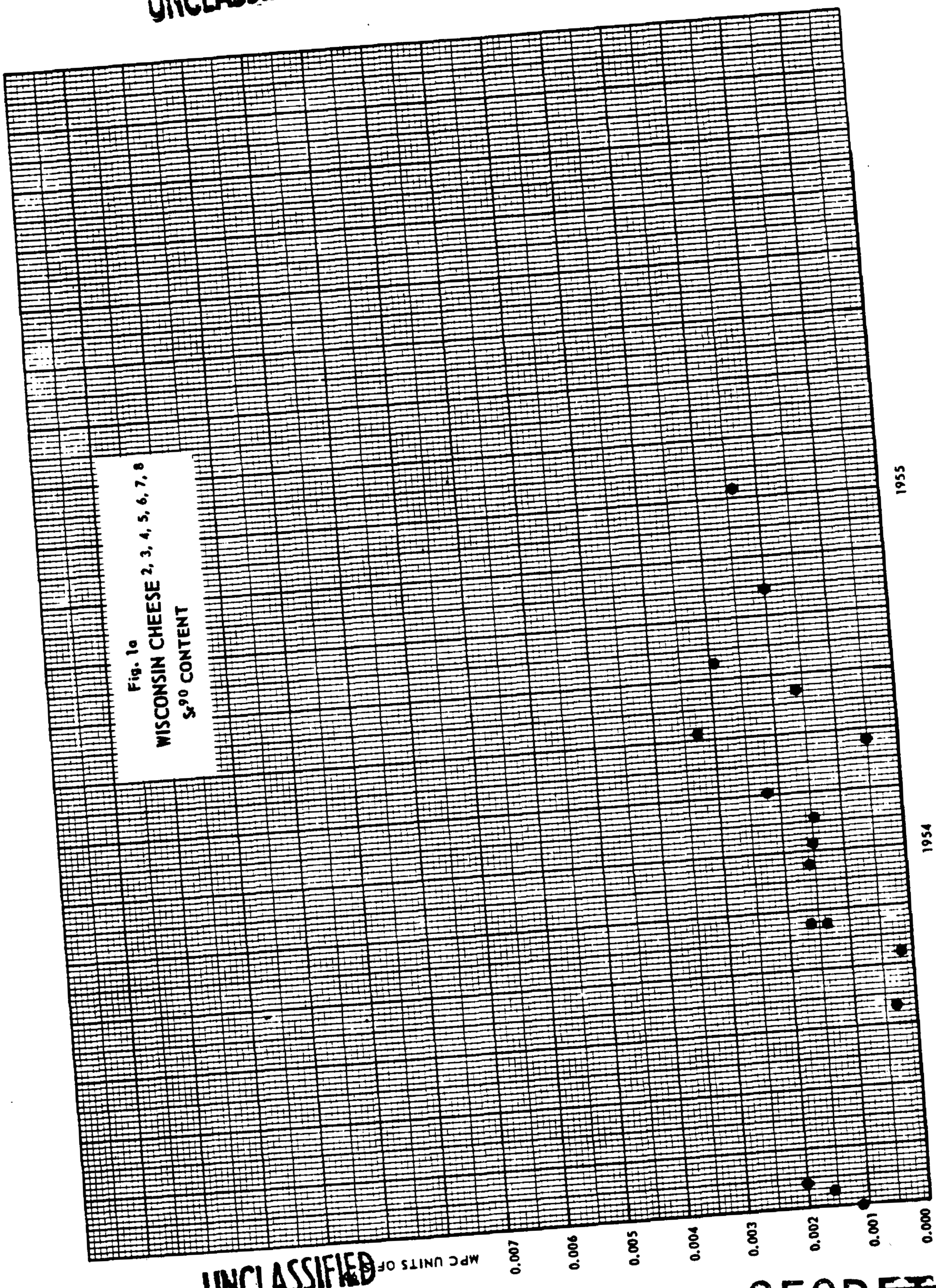

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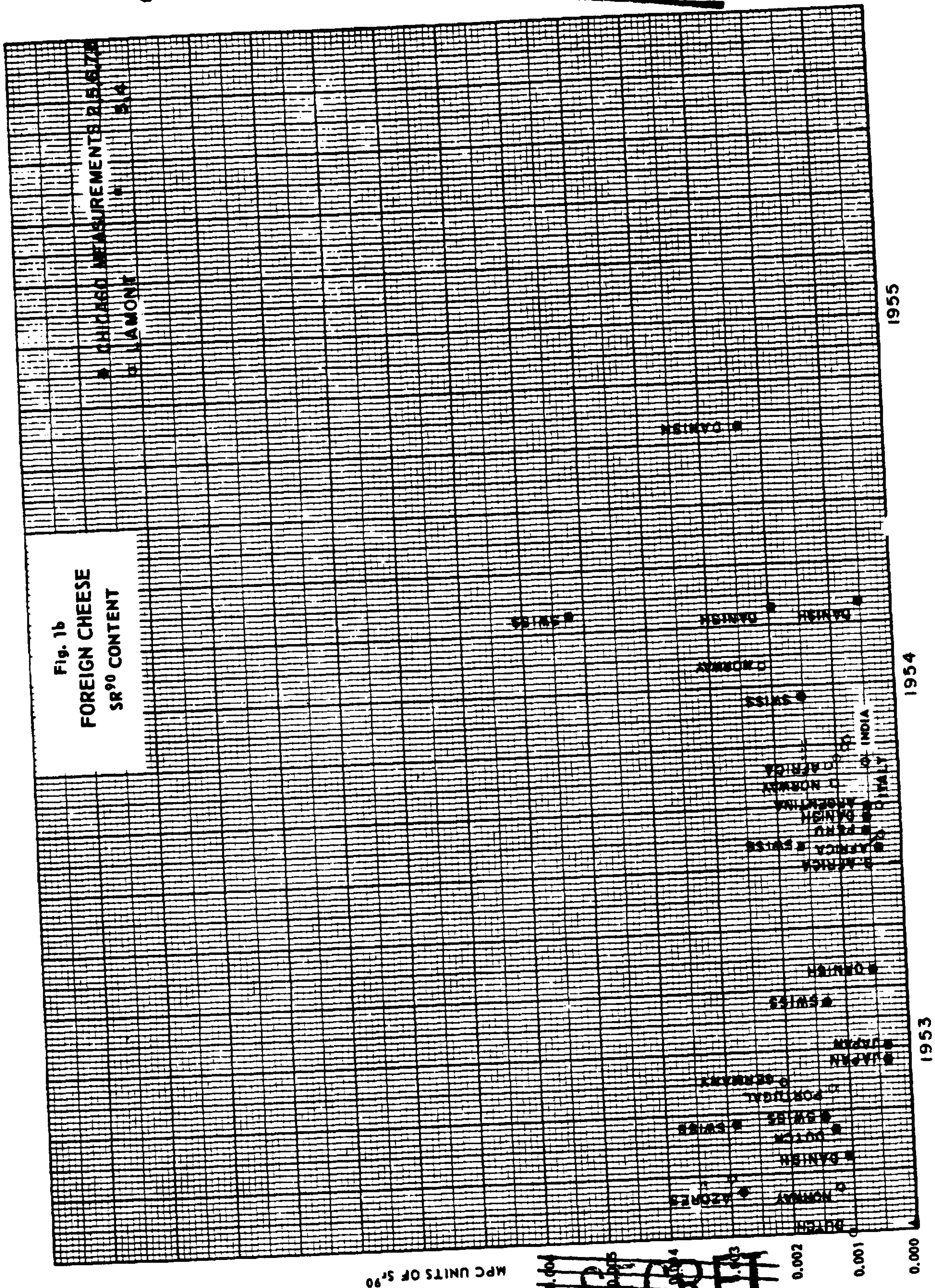

Fig. 1b
FOREIGN CHEESE
SR^{90} CONTENT

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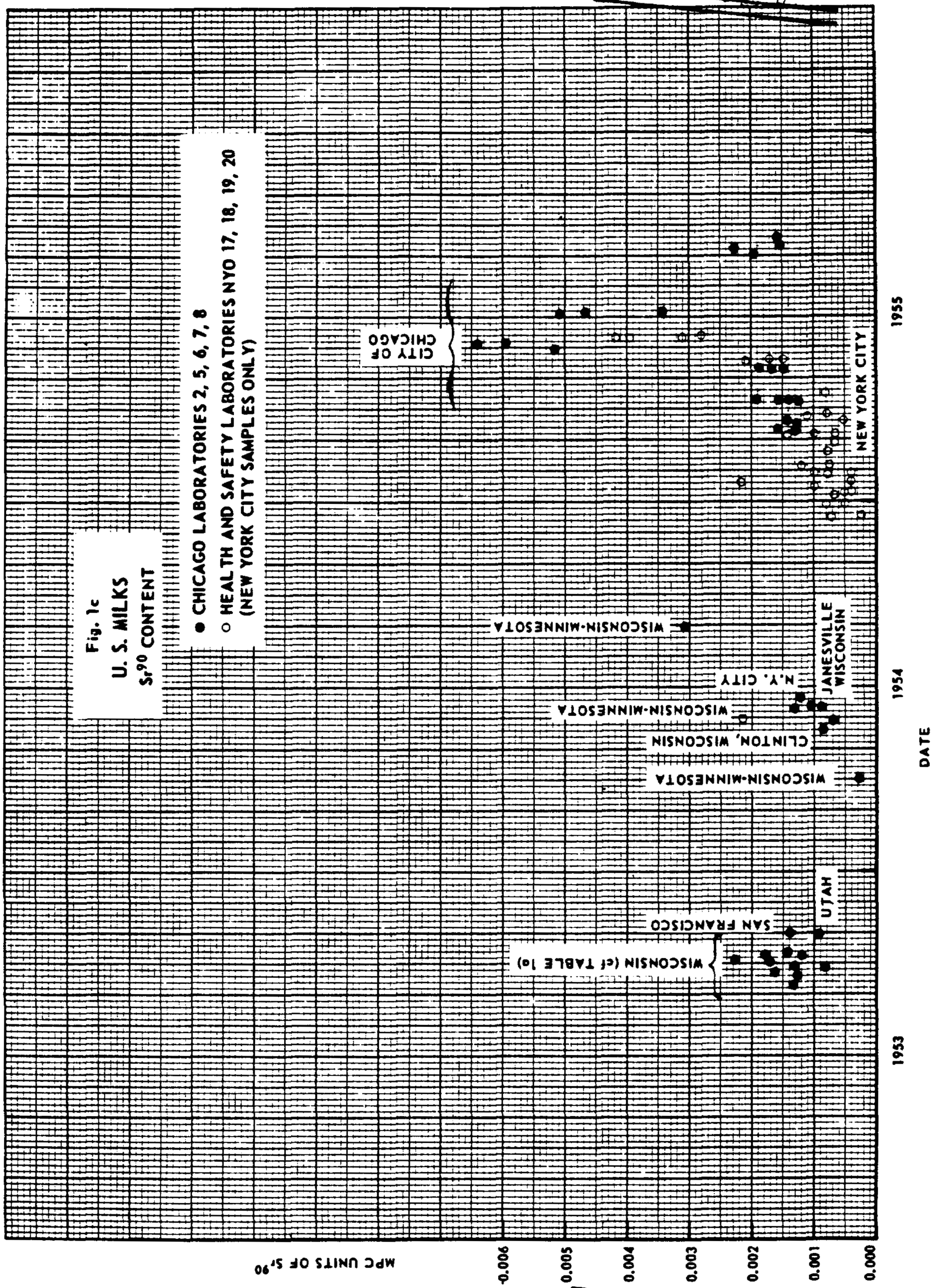

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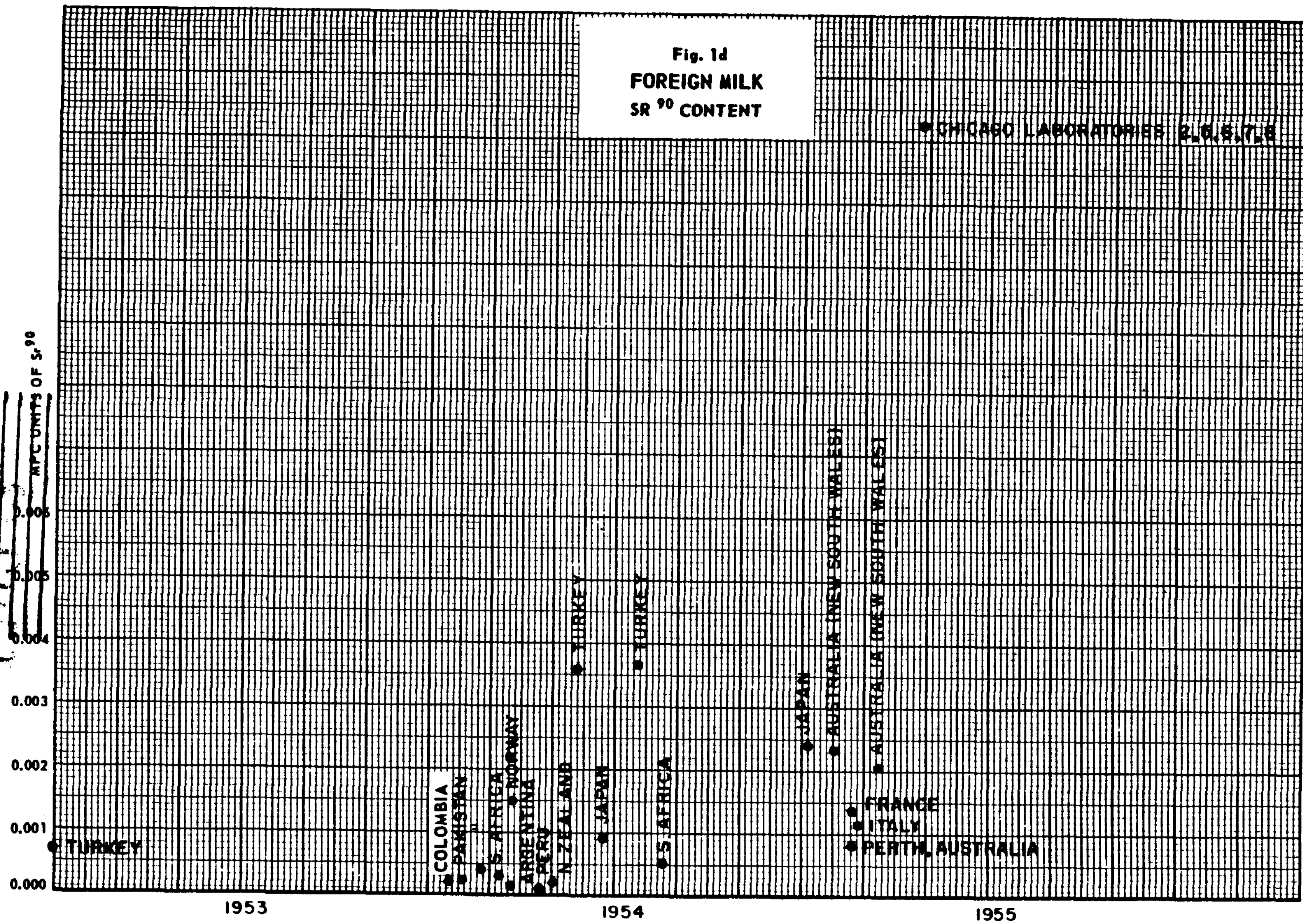

Fig. 1d
FOREIGN MILK
SR^{90} CONTENT

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The amount of radiostrontium found in humans is shown in Figs. 2a and b. The data show that the present Sr^{90} content probably averages somewhat less than one Sunshine Unit in young people. Apparently a number of barriers protect the human skeleton from this fallout radioactivity.

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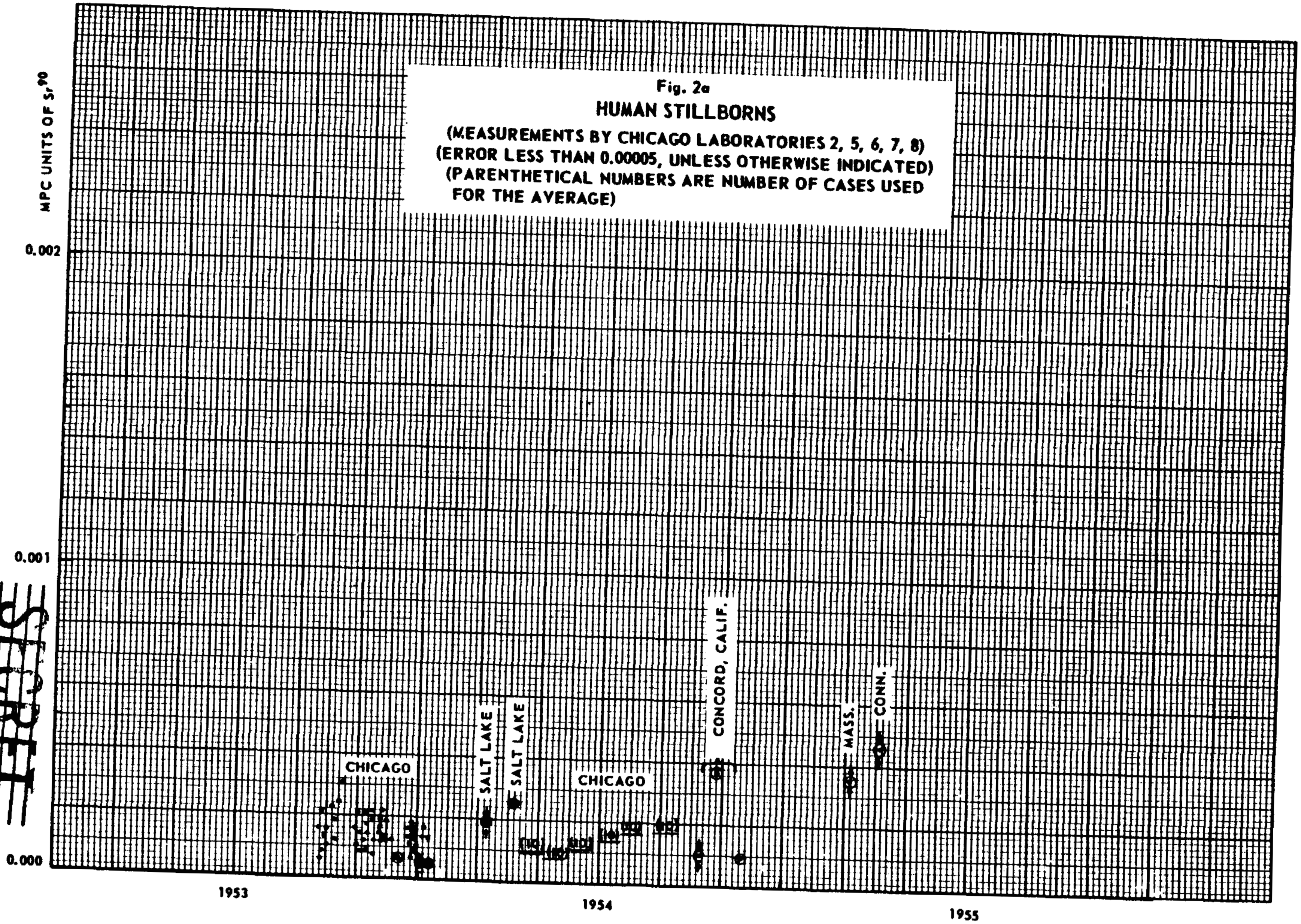

Fig. 2a
HUMAN STILLBORNS
(MEASUREMENTS BY CHICAGO LABORATORIES 2, 5, 6, 7, 8)
(ERROR LESS THAN 0.00005, UNLESS OTHERWISE INDICATED)
(PARENTHETICAL NUMBERS ARE NUMBER OF CASES USED FOR THE AVERAGE)

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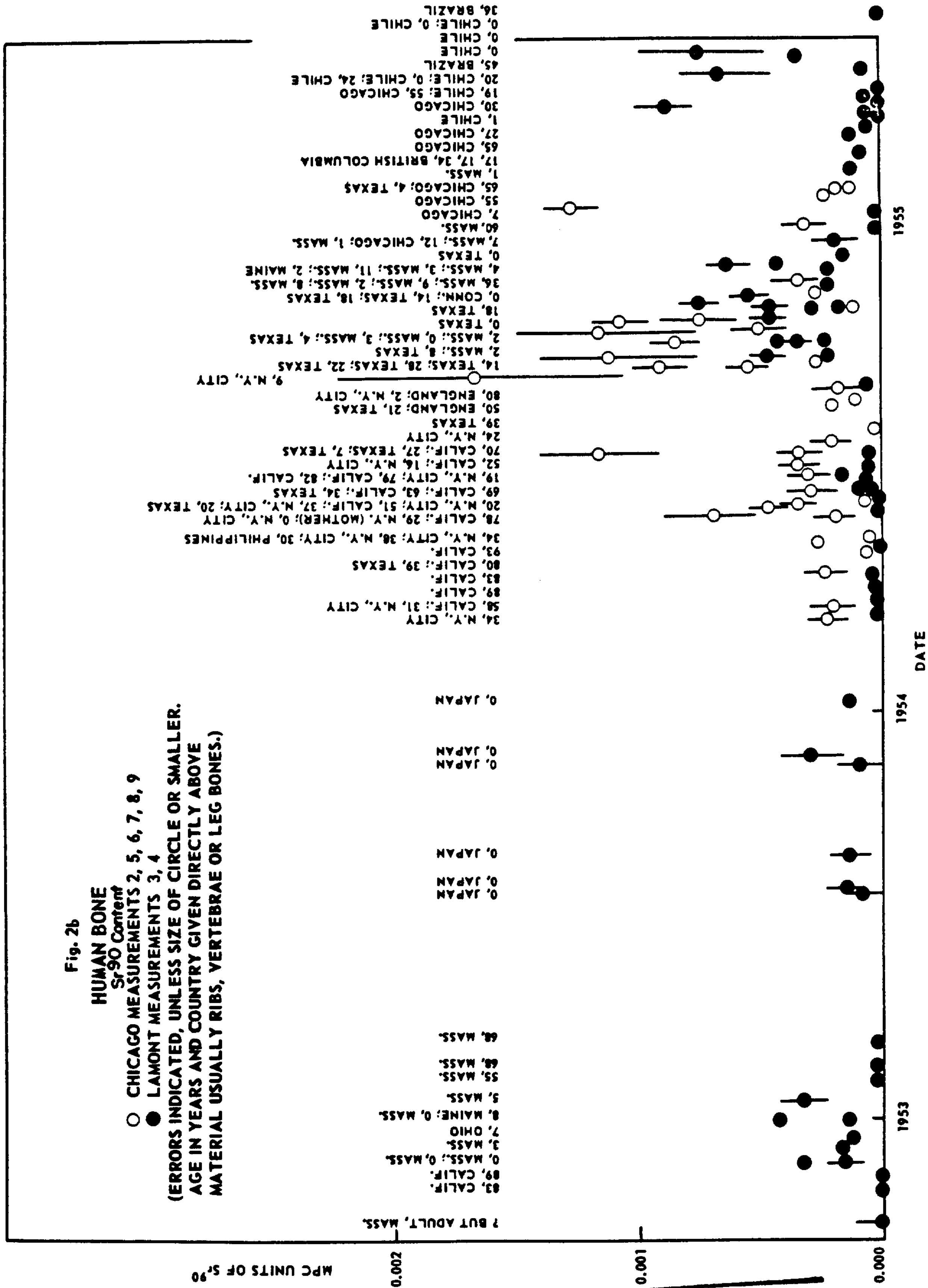

Fig. 2b
HUMAN BONE
Sr^{90} Content
○ CHICAGO MEASUREMENTS 2, 5, 6, 7, 8, 9
● LAMONT MEASUREMENTS 3, 4
(ERRORS INDICATED, UNLESS SIZE OF CIRCLE OR SMALLER.
AGE IN YEARS AND COUNTRY GIVEN DIRECTLY ABOVE
MATERIAL USUALLY RIBS, VERTEBRAE OR LEG BONES.)

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Measurements have been made on animals, principally cattle and sheep. These data are given in Figs. 3a and b. We see here that the contents are much higher than those for milk and human samples, apparently due to selective deposition of Sr in the animal bones, which protects the milk and thus human bone.

Data for foreign soil samples collected just before the Castle Test series are presented in Table 3 and Figs. 4a and b. From these data we deduce that the band around the earth bounded by the latitudes 60°N and 10°S shows a deposition of 0.8 megatons (MT) equivalent of Sr^{90} calculated at 3.7% fission yield for Sr^{90} in addition to some 0.4 MT which appears to be nearly uniformly deposited as would have been expected from a slow deposition from a large stratospheric reservoir. No evidence for longitudinal variation is apparent in Fig. 4b. Table 4 shows the total tropospheric deposition as calculated by subtracting the fallout expected 9/, 10/, 11/ in the immediate neighborhood of a few hundred miles from the test site. This number, probably about 1.4 MT, agrees well enough with the magnitude of the bump in the curve in Fig. 4a. The data in Table 1 showing 4.7 mc/mi^2 account for only 0.15 MT of local U. S. excess. The 1.4 MT figure is calculated by using a scaled height for each shot as given in Fig. 5 which correlates with an expected fallout not in the immediate neighborhood as shown in Fig. 6. This methodology 9/ apparently predicts the magnitude of local fallouts for sub-megaton weapons well enough.

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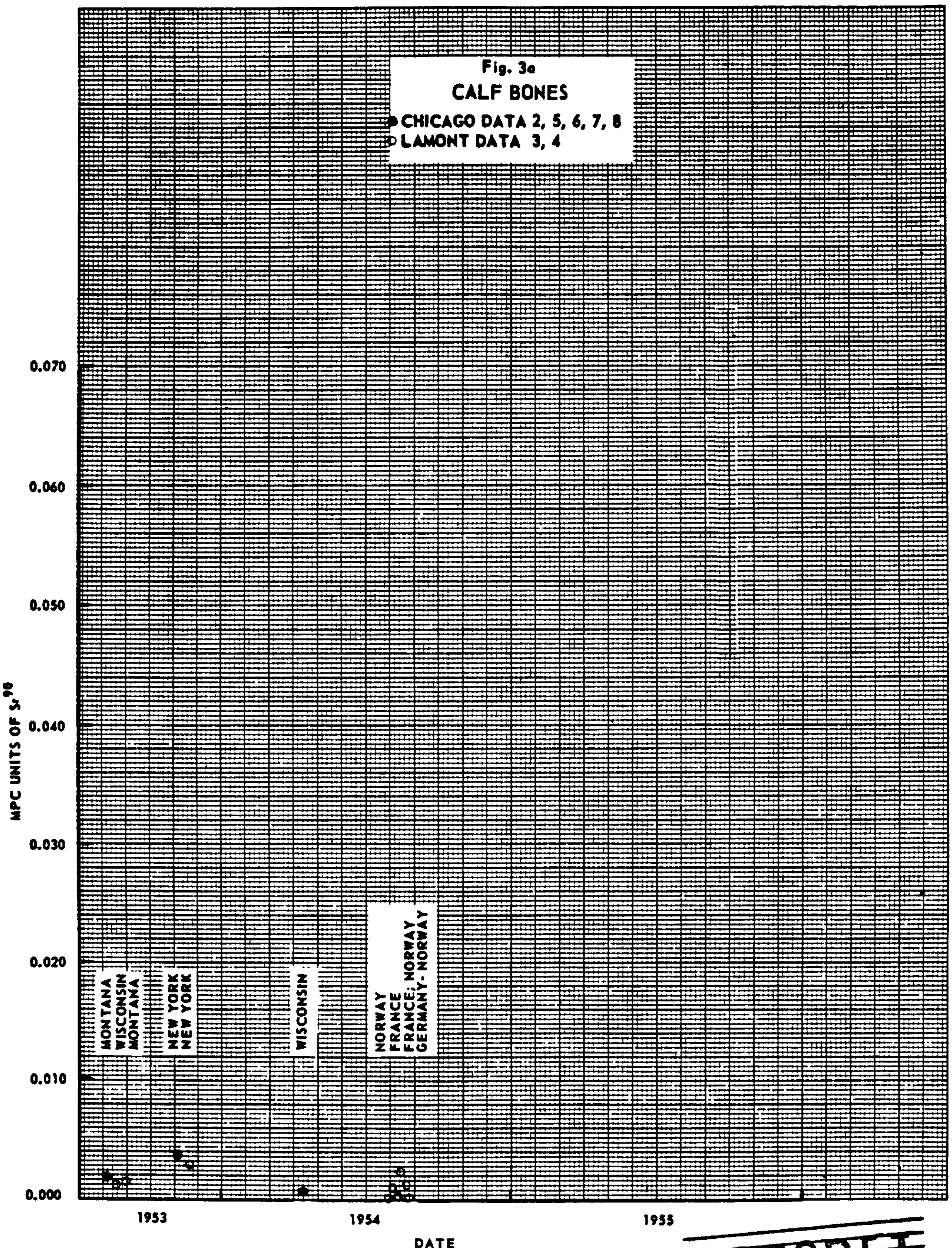

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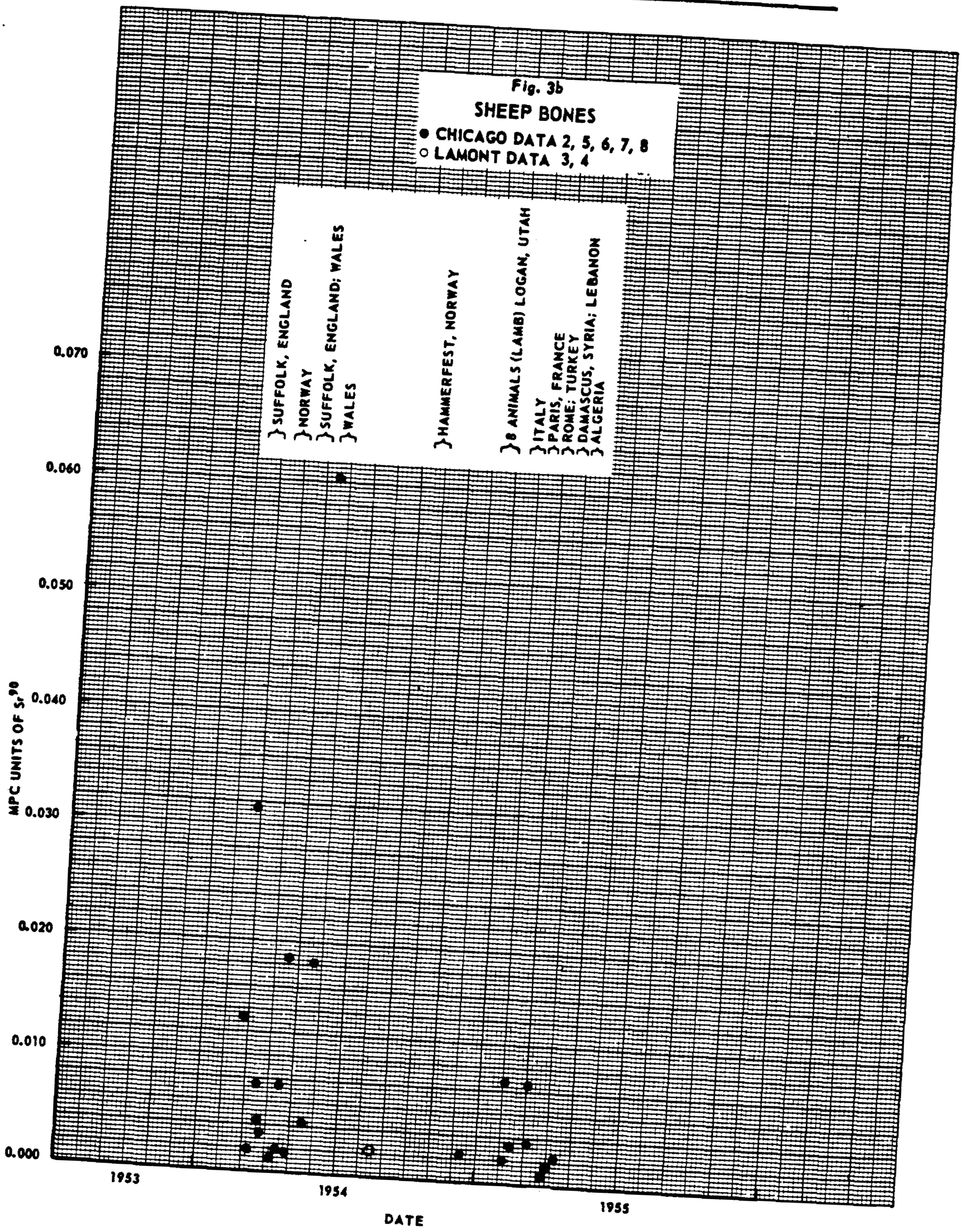
Fig. 3b
SHEEP BONES
● CHICAGO DATA 2, 5, 6, 7, 8
○ LAMONT DATA 3, 4
} SUFFOLK, ENGLAND
} NORWAY
} SUFFOLK, ENGLAND; WALES
} WALES
} HAMMERFEST, NORWAY
} 8 ANIMALS (LAMB) LOGAN, UTAH
} ITALY
} PARIS, FRANCE
} ROME; TURKEY
} DAMASCUS, SYRIA; LEBANON
} ALGERIA
MPC UNITS OF Sr^{90}
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
1953
1954
1955
DATE

TABLE 3

Sr^{90} CONTENT AND OTHER PERTINENT DATA

ON FOREIGN SOIL SAMPLES COLLECTED BEFORE CASTLE

Lat/Long	Location	Number	Date Sample Taken	Area of Sample (ft^2)	Depth of Sample (inches)	Calcium Extracted (In NH_4Ac Extraction) (Grams)	Weight of Sample Extracted, (Pounds)	Exchange-able Ca Analytical Method (me/100g)	Total Weight of Sample Taken (lbs.)	Calculated Exchange-able Ca in Sample (Grams)	Calculated Exchange-able Ca (g/ft^2)	(G/ft^2/in)	% Ca Ex-tracted in Col. 7	Sr^{90} Content (Sunshine Unit)	Sr^{90} Fall-out (mc/mi^2)
35°S/60°W	Buenos Aires, Arg. (8 miles apart)	54569	3/15/54	2	0-4	8.7	8	15.0	45.7	62.2	31.1	7.8	80	0.45 ± 0.03	0.39
"	Buenos Aires, Arg.	54570	3/15/54	2	0-4	6.6	8	10.2	45.7	42.3	21.2	5.3	89	0.44 ± 0.03	0.26
2°N/104°E	Bin Tong Park. Sing.	54571	3/4/54	2	0-4	0.01	8	0.4	40.6	1.5	0.73	0.13	3	≤ 50	≤ 1.0
"	Tengah Air Base, "	54572	3/4/54	2	0-4	0.3	8	0.4	42.5	1.54	0.77	0.19	100	22 ± 2	0.5
20°N/75°E	Field 1-64 mi., Poona, India	54573	3/9/54	2	0-4	37.6	8	60.1	72.8	403.	201.	50.	86	0.090 ± .008	0.5
"	Field 2-64 mi. Do	54574	3/9/54	2	0-4	40.8	8	64.2	48.1	280.	140.	35.	87	0.098 ± .013	0.38
28°N/75°E	New Delhi, India (4 miles apart)	54575	2/26/54	2	0-4	6.0	8	10.2	40.9	37.9	18.9	4.7	81	1.66 ± 0.08	0.87
"	New Delhi, India	54576	2/26/54	2	0-4	5.5	4	17.2	44.4	71.2	35.6	9.0	88	1.97 ± 0.10	2.0
30°N/75°E	Molir Village, Pakistan	54671	2/25/54	2	0-4	4.3	4	18.4	60.5	101.	50.5	12.6	64	0.27 ± .03	0.38
"	Hub River, Pakistan	54672	2/25/54	2	0-4	4.0	4	16.6	65.3	98.4	49.2	12.3	66	0.35 ± 0.04	0.48
52°N/0°	Rothamstead, Eng.	54675	4/1/54	7(est)	0-3	4.5	4	13.5	95.8	117.4	16.8	5.6	92	1.31 ± 0.07	0.61
5°N/75°W	Bogata, Columbia (plowed)	54715	3/1/54	2	0-4	4.3	4	13.8	29.9	37.5	18.7	4.7	86	0.67 ± .04	0.35
"	Bogata, Columbia (grass)	54716	3/1/54	2	0-4	4.8	4	13.9	51.0	64.4	32.2	8.1	95	0.91 ± .08	0.82
5°S/30°E	Leopoldville, Belgian	54717	3/1/54	2	0-4	2.4	4	4.6	51.1	21.3	10.7	2.7	All	0.92 ± .08	0.27
"	" " Congo	54718	3/1/54	2	0-4	4.5	4	13.2	69.4	83.2	41.6	10.4	94	0.21 ± .04	0.24
12°N/45°E	Aden Protectorate, SW Arabia	54421	3/1/54	2	0-4	9.6	8	23.7	32.0	68.9	34.4	8.6	56	0.51 ± 0.03	0.49
"	Do	54422	3/1/54	2	0-4	9.4	8	19.7	30.0	53.7	26.8	6.7	66	1.05 ± 0.10	0.78
60°N/45°E	Oslo, Norway (Walsh)	54412	4/27/54	2.21	0-2	9.8	8	17.0	16.2	25.0	11.3	5.7	79	1.51 ± 0.05	0.48
"	Oslo, Norway #1	54410	4/27/54	2.21	0-2	11.0	8	18.0	16.0	26.2	11.9	5.9	84	1.44 ± 0.06	0.48
32°N/0°	Beka'a Valley, Lebanon	54293	2/25/54	1.5	0-3	20.2	7	41.5	17.0	64.1	42.7	14.2	77	0.86 ± .05	1.0

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35°N/2°	Boghari, Algeria #3	54359	2/22/54	2.21	0-2	13.2	8	29.8	19.0	51.4	23.3	11.6	61	3.4 ± 0.08	2.2
"	Boghari, Algeria #1	54360	2/22/54	2.76	0-2	13.7	8	34.3	19.4	60.4	21.9	10.9	55	3.8 ± 0.1	2.3
"	Boghari, Algeria #2	54361	2/22/54	2.21	0-2	10.0	8	25.8	18.3	42.5	19.4	9.7	53	3.46 ± 0.08	1.9
35°N/40°E	Village 41 km SE of Damascus, Syria	54295	2/26/54	2.21	0-2	12.4	7	27.1	14.4	35.4	15.6	7.8	72	1.9 ± 0.08	0.82
"	Tel Muskan, Syria	54296	2/26/54	2.21	0-2	18.6	7	29.6	20.0	53.8	24.3	12.1	99	1.1 ± 0.10	0.75
52°N/0°	Ffostill,Breton,Wales	54415	4/?/54	2.78	0-2	8.0	8	11.4	11.4	11.8	4.27	2.1	97	3.3 ± .12	0.39
"	Montgomery,B.I.,Wales	54416	4/?/54	2.78	0-2	9.6	8	11.6	8.3	8.7	3.1	1.6	All		
"	Cardigan,B.I.,Wales	54417	4/?/54	2.78	0-2	0.3	5	1.3	10.2	1.2	0.4	0.2	50	97 ± 9.1	1.1
52°N/0°	Suffolk, Eng. #4	54418	4/?/54	1.74	0-2	15.2	7	37.2	16.6	56.1	32.2	16.1	64	1.37 ± .06	1.2
"	" Eng.,Pudding Crnr.	54419	4/?/54	1.74	0-2	18.1	8	38.0	16.8	58.0	33.3	16.7	66	0.89 ± .05	0.33
"	" " Old Orchard	54420	4/?/54	1.74	0-2	16.6	8	36.2	17.9	58.8	33.8	16.9	63	0.94 ± .09	0.39
28°N/75°E	New Delhi, India	531803	10/?/53	8 (est)	0-2	10.3	10	13.6	67.4	83.2	10.4	5.2	83	1.7 ± 0.01	0.49
13°N/80°E	Madras, India "A"	54357	3/?/54	2	0-4	5.4	7	7.6	66.0	45.5	22.8	5.7	All	1.21 ± 0.01	0.77
"	Madras, India "B"	54358	3/?/54	2	0-4	5.7	8	5.2	53.0	25.0	12.5	3.1	All	0.29 ± 0.03	0.10
45°S/170°E	New Zealand,Hutt Co.	531804	11/?/53	5 (est)	0-3	7.9	8.5	13.0	44.0	51.9	10.4	3.5	79	≤ 0.21	≤ 0.06
"	" " ,S.Canterbury	5485	1/18/54	5 (est)	0-3	6.5	9	10.8	47.2	46.3	9.3	3.1	74	≤ 0.18	≤ 0.05
"	" " ,Whangarei Co.	5471	1/18/54	5 (est)	0-3	0.9	8	1.7	37.7	5.8	1.20	0.4	75	2.51 ± .09	0.084
20°S/45°W	Belo Horizonte, Brazil (3 km apart)	54288	3/?/54	2	0-4	0.2	10	0.4	42.0	1.5	0.8	0.2	50	13.5 ± 1.25	0.30
"	Belo Horizonte, Brazil	54289	3/?/54	2	0-4	0.6	8	0.7	26.5	1.7	0.9	0.2	All	4.17 ± 0.3	0.10
35°S/75°W	Santiago, Chile	5472	12/?/53	30	0-1	10.2	8	27.2	50.4	124.5	4.15	4.1	51.5	≤ 0.33	≤ 0.04
30°S/30°E	Natal, S. Africa	54399	2/?/54	2	0-4	2.6	8	4.2	29.5	11.2	5.6	1.4	86.7	0.49 ± 0.08	0.076
"	Natal, " " ,3 mi SE	54400	2/?/54	2	0-4	1.7	8	1.2	47.0	5.1	2.55	0.6		9.80 ± 0.71	0.70
15°N/120°E	Philippine Islands	54401	2/26/54	2	0-4	14.8	8	18.6	48.4	81.7	40.8	10.2	All	1.47 ± 0.21	1.64
"	Philippine Islands	54402	2/26/54	2	0-4	3.5	8	5.6	51.7	26.3	13.1	3.3	85.4	20.1 ± 2.3	7.3

Samples collected and analyzed chemically by Dr. Lyle T. Alexander

All measurements made in Chicago Sunshine Laboratory, Refs. 2, 5, 6, 7 and 8

Average: 8.1 ± 0.8 g Ca/ft²/in = 8.8 ± 0.9 mg Ca/cm²/in

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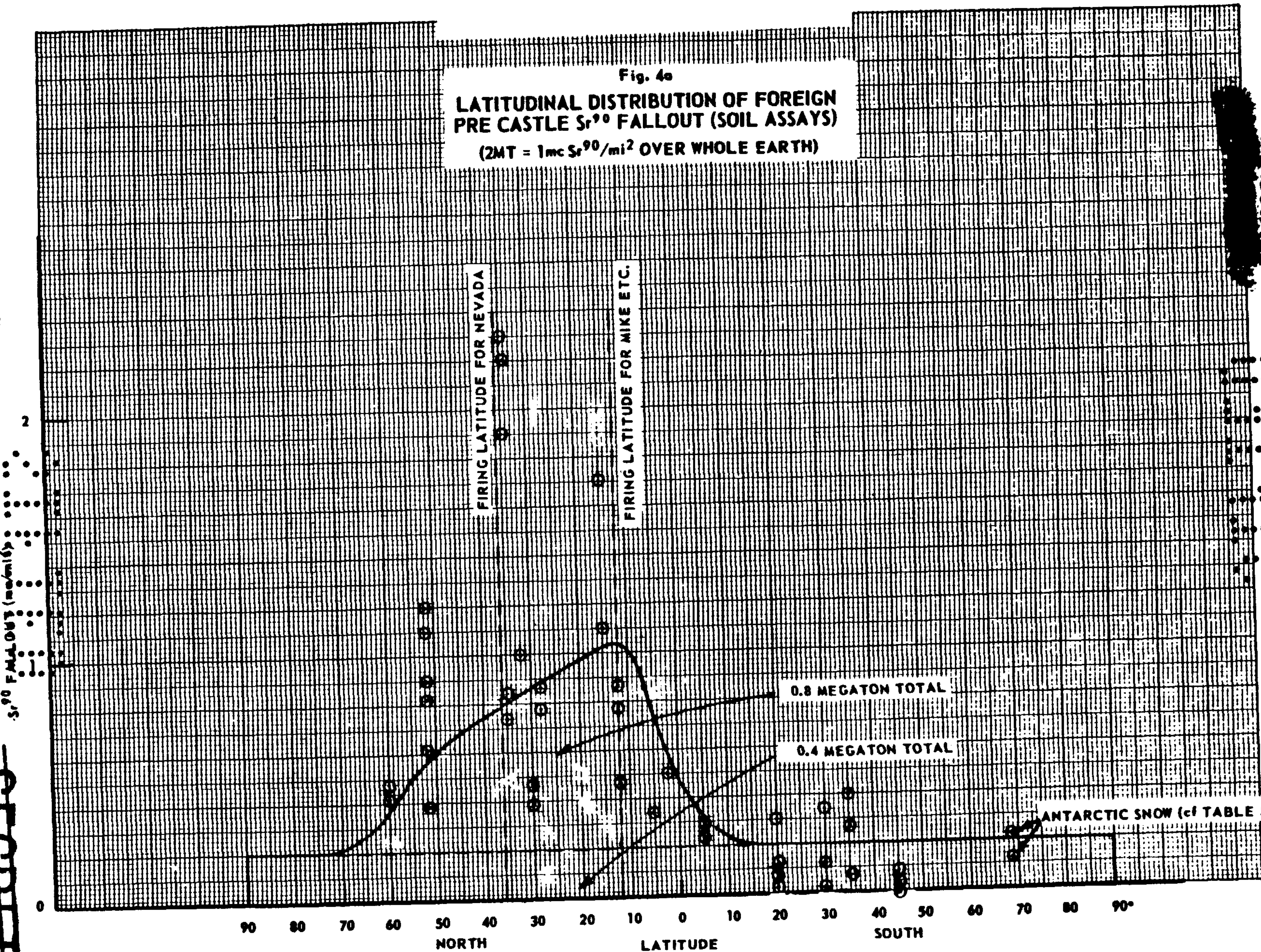

Fig. 4a

LATITUDINAL DISTRIBUTION OF FOREIGN PRE CASTLE Sr^{90} FALLOUT (SOIL ASSAYS)

(2MT = 1mc Sr^{90}/mi^2 OVER WHOLE EARTH)

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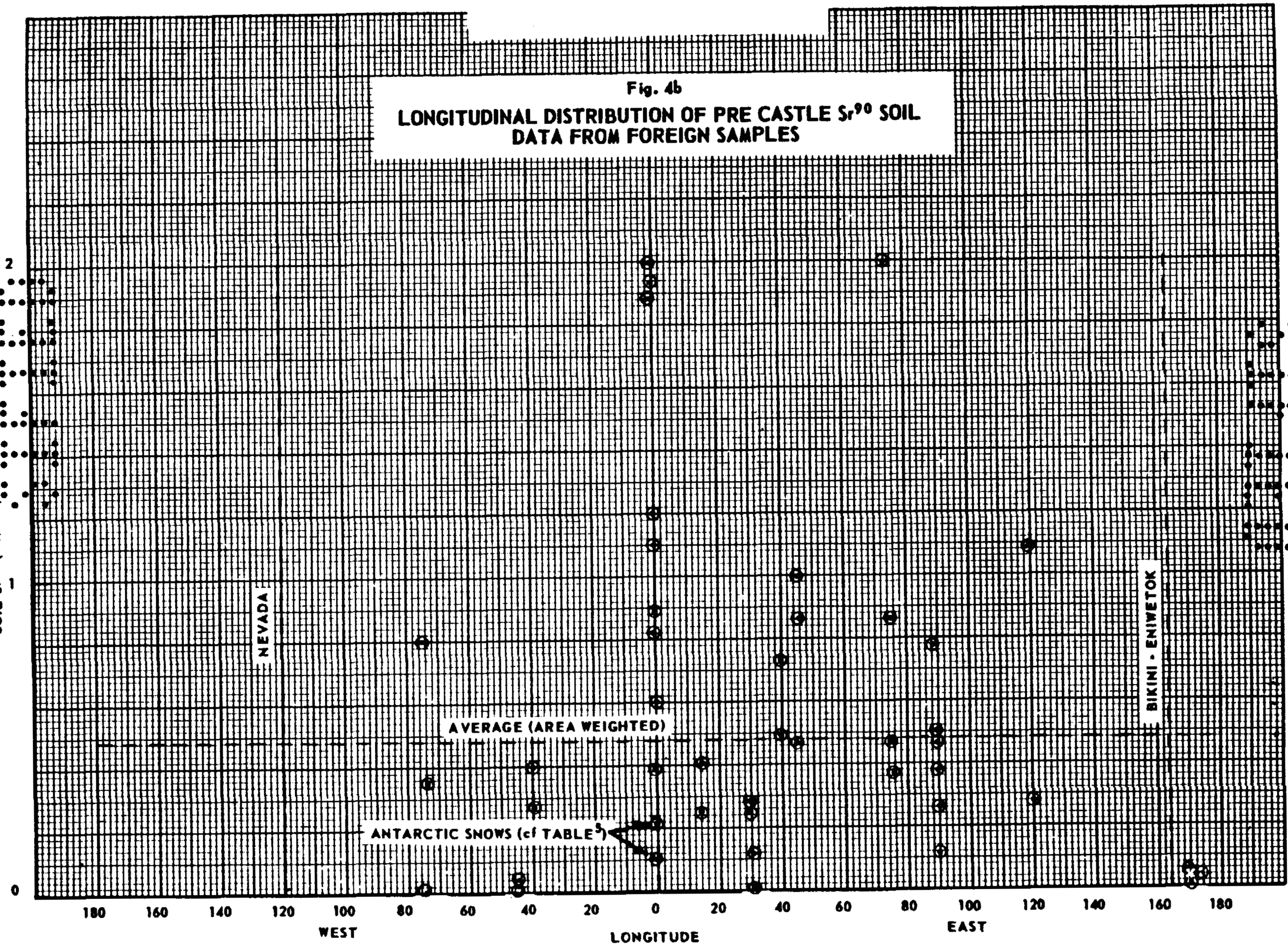

Fig. 4b

LONGITUDINAL DISTRIBUTION OF PRE CASTLE Sr^{90} SOIL DATA FROM FOREIGN SAMPLES

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TABLE 4
PRE-CASTLE
EXPECTED TROPOSPHERIC FALLOUT
(Bombs less than 1 MT Yield)

(Col. Lulejian's formula.) "Radiation Hazards During Atomic Warfare," A.R.D.C. November 1954

Test	Total Yield (KT)	Distant Fallout (KT)	Height of Burst (Ft.)
Russian*	[redacted]	[redacted]	(*Assumed surface burst.)
British*			
U.S.			
Ranger (Nevada 1951)	1.3	1.3	1060
	8	8	1080
	1	1	1080
	8	8	1100
	22	22	1435
Buster-Jangle (Nevada 1951)	3.5	3.5	1118
	14	14	1111
	21	21	1417
	31	31	1314
	1.2	0.05	0
Tumbler-Snapper (Nevada 1952)	1	1	793
	1	1	1109
	31	31	3447
	19	19	1040
	13	11	300
	12	11	300
	17	14	300
	17	14	300

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TABLE 2 (Cont'd)

U.S.			
Upshot-Knothole	18	16	300
(Nevada 1952)	24	18	300
	0.2	0.2	
	11	11	6020
	0.3	0.3	100
	27	20	300
	52	36	300
	26	26	2423
	32	24	300
	15	15	524
	60	60	1334
Crossroads	25	25	518
(Pacific 1946)	23.5	1	- 90' (water)
Sandstone	36	22	200
(Pacific 1948)	50	30	200
	20	13	200
Greenhouse	82.3	54	300
(Pacific 1951)	47	33	300
	250	110	200
	45.7	27	200
Ivy	550	530	1480
(Pacific 1952)			
(Mike omitted)			
TOTAL		1400 KT	

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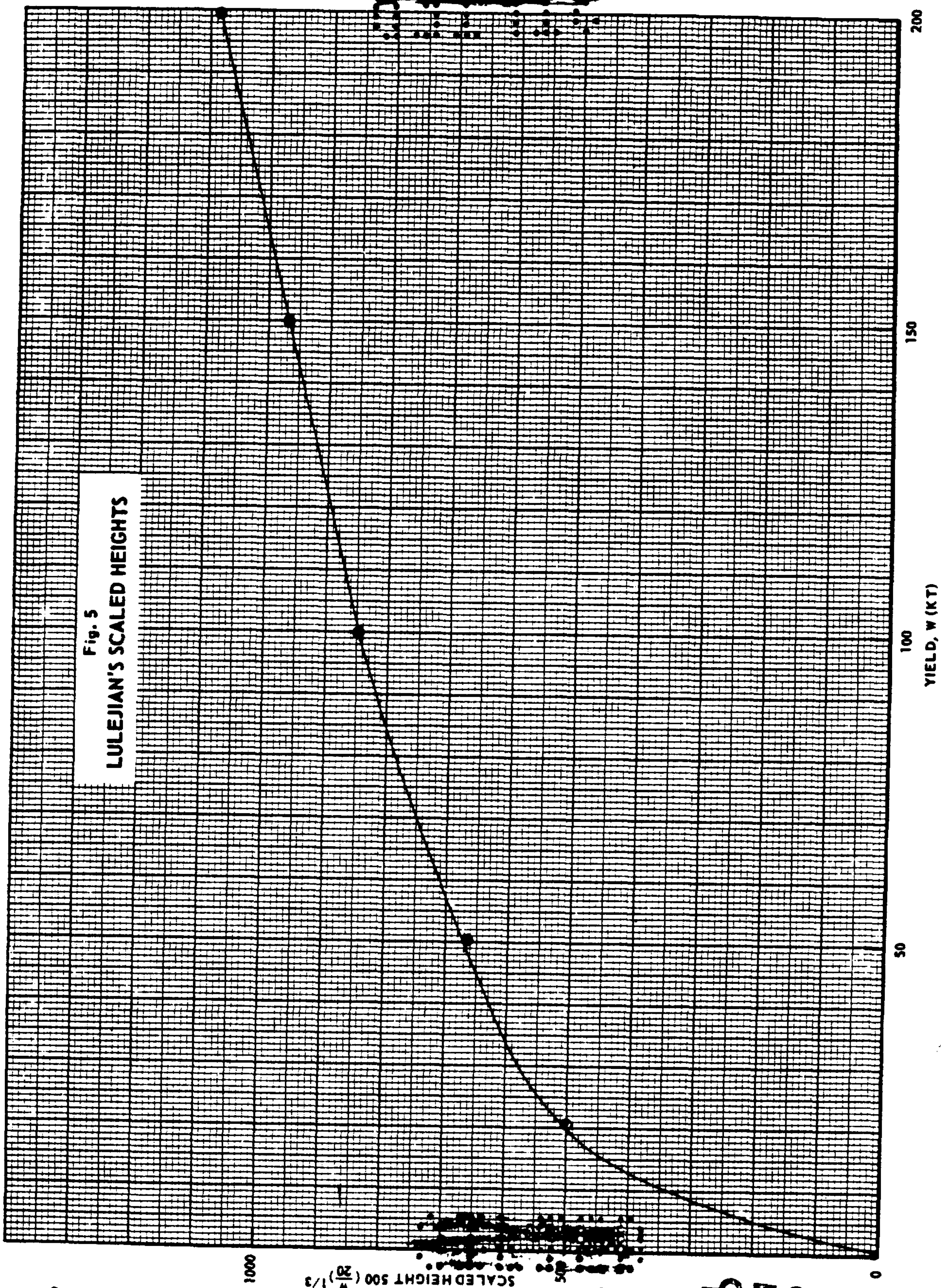

Fig. 5
LULEJIAN'S SCALED HEIGHTS

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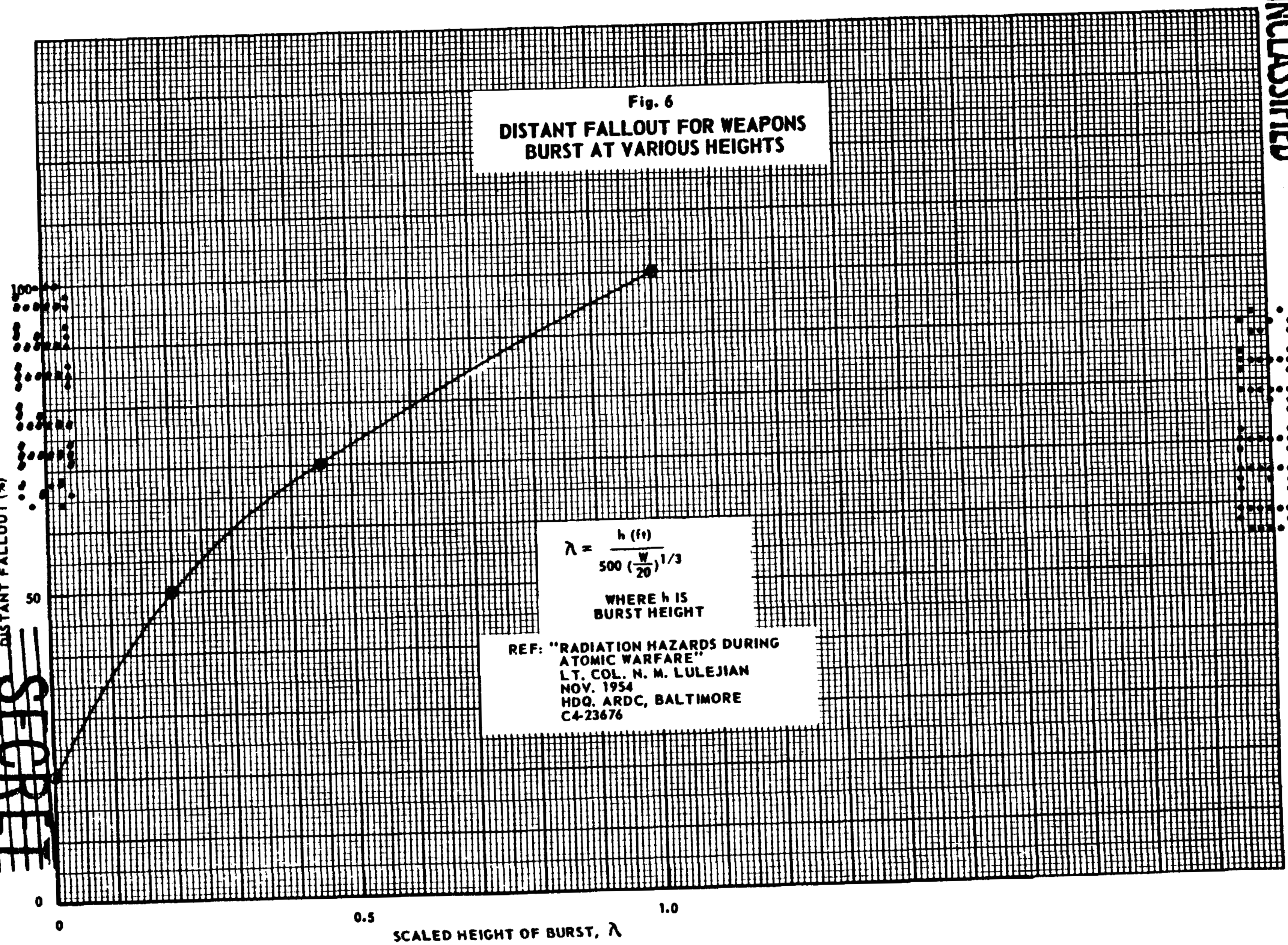

Fig. 6

DISTANT FALLOUT FOR WEAPONS BURST AT VARIOUS HEIGHTS

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The actual heights of rise of the bomb clouds are shown in Fig. 7. These data are the basis for the assumption that all distant fallout from megaton weapons occurs from a stratospheric reservoir while that from those of less than megaton yield occurs from the troposphere. Actually, as shown, the height of the tropopause varies with season so the season must be considered in the assignment. During the Pacific tests it has been near 55,000 feet[10] so our classification has validity in this respect.

The total stratospheric inventory before Castle then should consist of the 0.84 ± 0.1 MT contribution made by Mike [

surface shot from a coral island in the Castle series, described later, cf. Tables 12 to 16 (inc.) and Figs. 11 to 15 (inc.)], less the fallout since November 1952.

Two of the most important data in Figs. 4a and b are the two from the Antarctic series. The samples were snow cores collected for the Chicago Sunshine Laboratory and for cosmic ray tritium (T) analysis,[12], [13], [14] by Mr. Paul Humphrey of the U. S. Weather Bureau in January and February 1955 at Admiral Byrd Bay (69°34'S; 00°41'W), at Atka Bay (70°35'S; 08°06'W), and at Little America III. The data are given in Tables 5 and 6. Table 5, Part A, gives the Sr^{90} and T contents of surface snow at four locations. From the T concentrations and the expected T production rate in this

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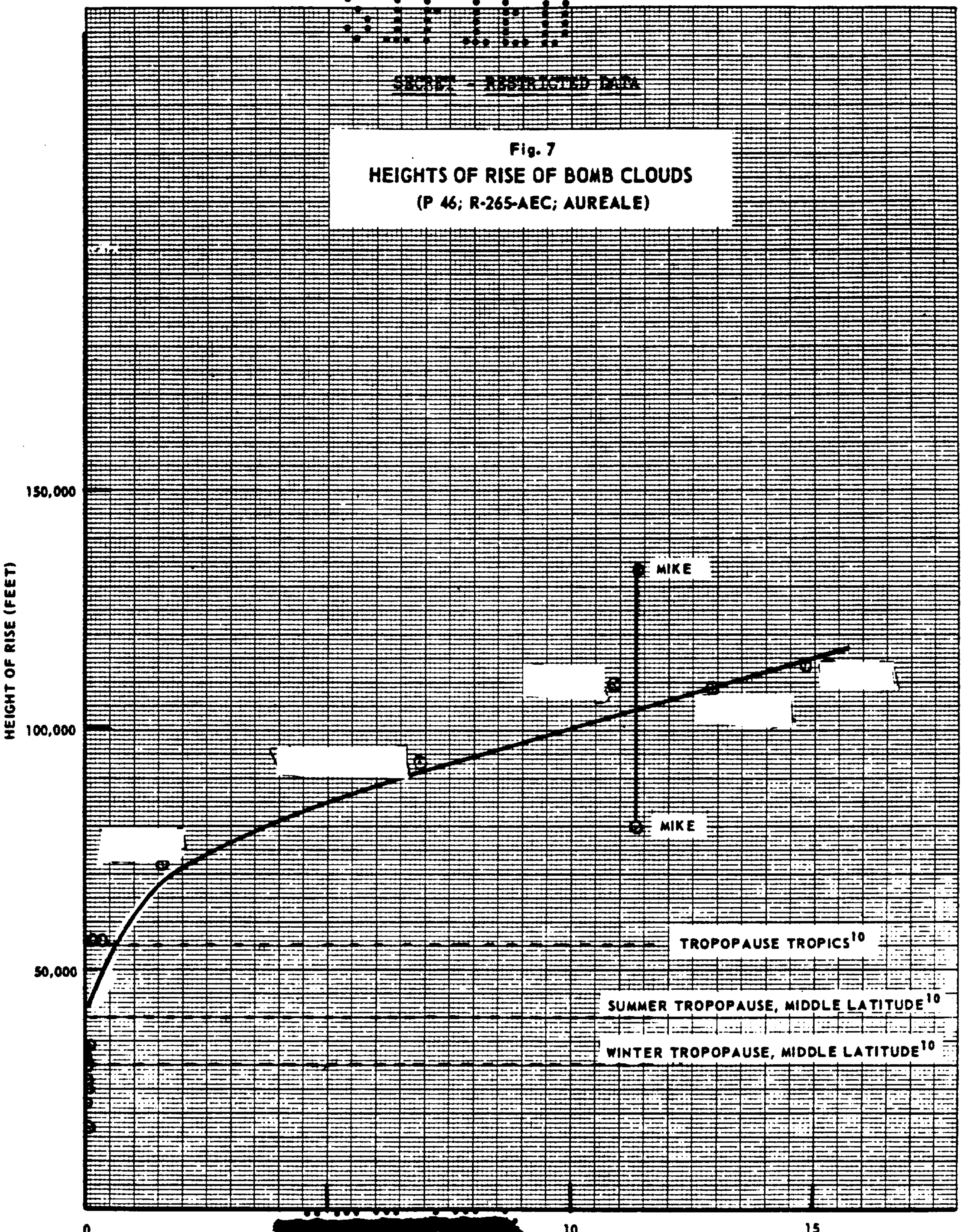

Fig. 7
HEIGHTS OF RISE OF BOMB CLOUDS
(P 46; R-265-AEC; AUREALE)

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TABLE 5

POST-CASTLE Sr^{90} FALLOUT IN ANTARCTICA

A. Surface Snow.

Date	Location	Sr^{90} (dpm/liter)	T (Atoms/10^{18} H's)
January 15, 1955	Near Quonset, Little America III	3.2 ± 0.3	14.1 ± 0.6
January 17, 1955	One-half mile east, Little America III	3.1 ± 0.7	7.5 ± 0.6
February, 1955	Atka Bay, 6 miles inland on shelf (70°35'S; 08°06'W)	5.3 ± 0.5	19.2 ± 0.8
February 19, 1955	Admiral Byrd Bay (69°34'S; 00°41'W)	2.0 ± 0.2	24 ± 5
		3.4 ± 0.5	14 ± 3

B. Sr^{90} Precipitation rate in January and February 1955.

Annual Snow Precipitation Rate from Tritium Assay[13],[14] and 0.59 T's/cm^2/sec as the expected antarctic cosmic ray tritium production.

$$\rho = \frac{4.7 \times 0.59}{14} \text{ meters/year} = 7.8'' \pm 2'' \text{ of water.}$$

Sr^{90} Rate of Precipitation

3.4 ± 0.5 dpm/liter = 62 dpm/ft^2/yr for 7.8" water/year

= 0.8 ± 0.2 mc/mi^2/yr

TABLE 6

PRE- AND POST-CASTLE Sr^{90} FALLOUT AT ADMIRAL BYRD BAY

(69°34'S; 00°41'W)
(Collected 2/19/55)

Snow Core

Age (7.8" water/yr)	Depth (ft.)	Density	Sr^{90} (dpm/liter)	T (Atoms/10^{18}H's)	Sr^{90} Rate* (mc/mi^2/yr)
0 - .54 yrs.	0 - 1	.35	1.95 ± 0.20	24 ± 5	.46
.54 - 1.04 yrs.	1 - 2	.32	1.7 ± 0.2	12.5 ± .8	.40
1.04-1.52 yrs.	2 - 3	.30	0.48 ± 0.04	13.5 ± .7	.11
1.52-2.16 yrs.	3 - 4	.41	0.90 ± 0.06	---	.21

*Assumed annual precipitation 7.8" water/yr on basis of T contents of surface waters, cf. Table 5.

region[12/], [13/], [14/] (T produced in the Castle test itself was precipitated out in a few weeks and never entered the southern hemisphere because of the large amount of water taken into the cloud with which it became mixed.[36/]) we determine the annual precipitation to be 7.8 ± 2 inches of water. This calculation together with that for the January-February 1955 Sr^{90} precipitation rate of 0.8 mc/mi^2/yr are given in Part B. of Table 5. The result for the annual precipitation agrees well with direct observation by the Atka Expedition, and by Mr. Humphrey personally.[15/] At Little America IV, direct observation showed that the floor of the tent projecting from the ice front was beneath only 7 or 8 feet of snow after roughly seven years. Since the density of the snow was about 0.35 this would correspond to about 5 inches annual precipitation. Other observations[15/] checked this general magnitude. In Table 6 a core taken at Admiral Byrd Bay was measured for both Sr^{90} and T. From these data we observe the Pre-Castle fallout rates of 0.11 and 0.21 Sr^{90} mc/mi^2/yr. The surface rate at this site is 0.43 which is less than the general average in the area for January and February 1955 of 0.8 mc/mi^2/yr -- as shown in Table 5 -- so it may be that the Pre-Castle values at this site are low also and should be increased by the ratio 0.8/0.43 or by 90 percent to 0.2 and 0.4., respectively.

The average Sr^{90} content of rain and snow in the Chicago area since the fall of 1952 was calculated by weighting each datum by the total rainfall observed in the particular storm. The data on

the Sr^{90} content of Chicago rain are given in Fig. 8[2,5,6,7,8] (It is necessary to note that these collections were made without cleaning off the roof on which the rain fell so there may be more nearly total fall-out measurements than rain carried fallout data.) It is clear that large fluctuations can occur in individual storms. However, these extremes were in general of low total rainfall so the effect on the average is small. It is interesting that the Antarctic snows have about the same Sr^{90} content as the average Chicago rain of Fig. 8. We recall that precipitation there is only 1/5 to 1/4 of that in Chicago. According to the mechanism espoused in this paper, these fluctuations are to be expected because the fallout from the stratosphere is thought to be steady and continuing, and the washing out by rain is expected to carry down the fallout accumulated since the last precipitation from the particular air mass involved. Many of the rain samples illustrated in Fig. 8 and listed in Refs. 2, 5, 6, 7, and 8, have been measured for T as well[12,13,36] so further correlations of the type described above for Antarctic snow (Tables 5 and 6) can be made.

In Tables 1 and 2 the Sr^{90} content of soils in the Midwest region of the U. S. were shown to have an assay of 4.7 mc/mi^2 in October 1953. The total from rains in the preceding year was only 1.5 mc/mi^2, according to Fig. 8, so we have to expect about 3 mc/mi^2 to have been deposited prior to Ivy by direct fallout most reasonably from tropospheric debris. The total fired in Nevada prior to this time and which would not have fallen out in the immediate vicinity of the test site (cf. Figs. 5 and 6 and Table 4) was 212 KT for the Operations Tumbler-Snapper and Buster-Jangle together. If this were all deposited in the U. S. it would

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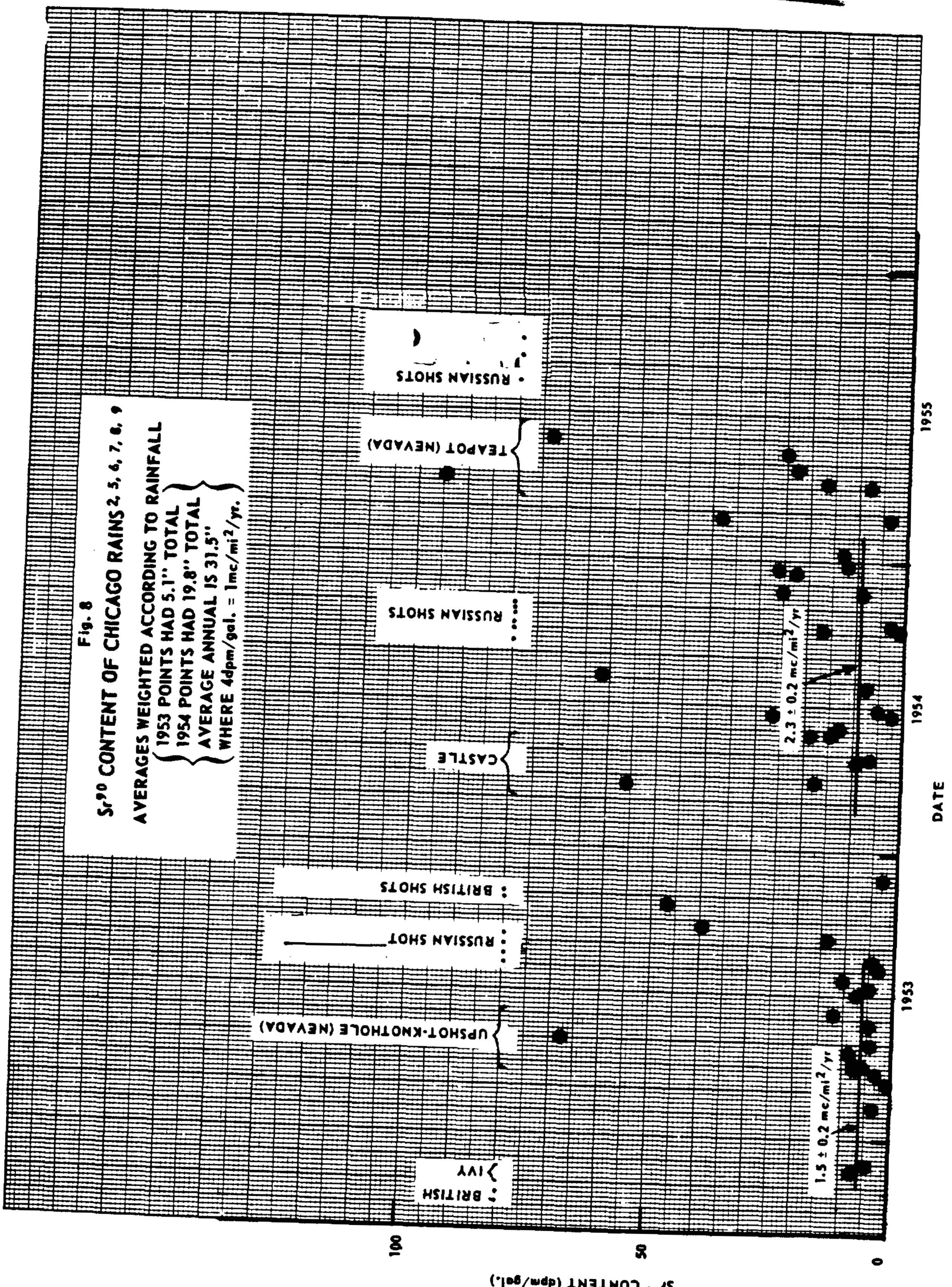

Fig. 8

Sr^{90} CONTENT OF CHICAGO RAINS 2, 5, 6, 7, 8, 9

AVERAGES WEIGHTED ACCORDING TO RAINFALL

1953 POINTS HAD 5.1'' TOTAL

1954 POINTS HAD 19.8'' TOTAL

AVERAGE ANNUAL IS 31.5''

WHERE 4dpm/gal. = 1mc/mi²/yr.

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amount to about 7.0 mc/mi^2. It seems not unreasonable that perhaps about half was deposited in the U. S. so we may tentatively conclude that the Pre-Castle rain and soil assays in the U. S. agree with each other and the overall mechanism and predict the Upshot-Knothole with 227 KT of distant fallout and Teapot with 169 KT should have added about 5.6 mc/mi^2 to the 4.7 in October 1953 and to the 3.0 mc/mi^2 of stratospheric fallout for the intervening period for a total of 13.3 mc/mi^2 expected in the spring of 1956 in the U. S.

The efficiency with which rain removes fallout from the air through which it passes probably is high. One knows on simple physical grounds that as little as 0.1 inch of rain will traverse at least 90 percent of the air volume lying below the layer in which the rain originates so that 90 percent of all particles which can be swept up by a falling raindrop will be carried down by such quantities of rain. On the point as to whether fallout is likely to be deposited by rain, we note that R. H. Wilkening[39/] showed that the decay products of the radioactive gas Rn which in themselves are isotopes of non-gaseous elements are found affixed to particles of diameters between 20 and 800 angstrom units (0.002 to 0.080 microns) -- a submicroscopic range not at all unlikely for the radioactive fallout stored in the stratosphere.[1/] The velocity of fall for such particles would be very small and in this respect quite compatible with the long stratosphere storage times indicated by the Project Sunshine data. Blifford, Lockhart and Rosenstock[37/] studied the concentration of the Rn decay products in rainfall in

the Washington, D. C., area and concluded that rain was the mechanism by which the particles containing these products was precipitated and that the average time the decay products spent in the air before being precipitated was only 15 days, approximately. O. Haxel and G. Schumann[38] found this time in Heidelberg, Germany, to be about 4 days, and Damon and Kuroda[40] concluded that Blifford et al were correct in attributing the precipitation of the aerosol carrying the Rn decay products to rain, their conclusion being based in part on additional data they had taken. The average time spent by water in the air was found by Libby and von Buttlar[13] to be between 5 and 14 days.

For these reasons it seems very likely that rainfall or snowfall carries down a major part of the fallout which comes from the stratosphere and probably is a very important mechanism for that part of the tropospheric fallout material which does not fall out in the first few hours or day or two after the detonations. Of course the whole question can be settled by direct experiment in which a correlation between rainfall and total fallout is sought. The present data seem to favor the hypothesis. This conclusion and prediction seems to be borne out by Table 7 which presents the total Sr^{90} content of the top 2" of typical U. S. soils collected in October 1955 and leached at room temperature for 30 minutes with 6N HCl.

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TABLE 7

Sr^{90} FALLOUT ACCUMULATION IN TOP SOIL (0-2") IN U.S. IN 1955

Sampled September 23-October 20, 1955
(Data by E. P. Hardy and R. S. Morse of
Health and Safety Laboratory, NYO, Personal Communication)

Station	Measured dpm/ft^2
La Guardia	310*
	350 ± 21
	550 ± 16
Binghamton	710 ± 16
Philadelphia	450 ± 19
Rochester	550 ± 20
Jacksonville	470 ± 20
Atlanta	530 ± 12
Detroit	640 ± 21
New Orleans	470 ± 14
Memphis	900 ± 20
Des Moines	540 ± 13
Rapid City	1070 ± 21
Seattle	400 ± 15
Boise	1160 ± 23
Albuquerque	270 ± 14
	290 ± 20
Grand Junction	280 ± 14
Salt Lake City	860 ± 18
Los Angeles	120 ± 12
Average	578
or	7.3 mc/mi^2

Probable additional Sr^{90} in lower layers to be released by additional leaching may raise this about two-fold.

*This datum was obtained by Dr. J. L. Kulp, Lamont Geological Observatory, Columbia University. ~~The procedure was different~~ from NYO's. Personal communication.

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Table 8 shows data obtained in the Chicago Laboratories on the Sr^{90} contents of Rivers and Lakes. It is clear that these are much lower than those of the rain from which they are derived. For example, from Fig. 8 we should estimate that the average rain in the Chicago area in the summer of 1953 had a Sr^{90} content of about 7 dpm/gal. From Table 1 for the domestic Pre-Castle soil contents and Figs. 4a and b for foreign Pre-Castle soil contents, we estimate that the European rain averaged about 3 dpm/gal. The four rivers: Mississippi, Mosel, Seine, and Danube show less than five percent of this; hence, we conclude that the Sr^{90} in rain is removed by the soil before the water runs off to the rivers and lakes. This fact agrees, of course, with the sharp localization of the Sr^{90} in top two inches of soil, cf. Tables 1, 2 and 3.

Examination of the data in Tables 2 and 3 on the Sr^{90} content of the exchangeable Ca in soils shows that there is a strong tendency for the lowest activity per unit weight of exchangeable Ca (smallest number of Sunshine Units) to occur in calcium-rich soils and vice versa as would be expected, of course, if the fall-out rate were uniform. This situation is displayed graphically for the Pre-Castle soil data in Fig. 9.

For years the Health and Safety Laboratory of the New York Operations Office of the AEC, Mr. Merril Eisenbud, Manager, with the cooperation of the United States Weather Bureau, has been collecting fallout data by use of gummed papers of 1 square foot area which are laid flat for a certain time out in the open away from buildings.[16] After the exposure, the paper is folded and

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TABLE 8

Sr^{90} CONTENT OF RIVER AND LAKE WATERS[2/, 5/, 6/, 7/]

	Sr^{90} Content (dpm/gal)
Lake Michigan, October 27, 1953	0.39 ± 0.08
Mississippi River, Memphis, February 4, 1953	1.13 ± 0.16
Mississipi River, St. Louis, April 17, 1953	< 0.77 ± 0.18
Mosel River, Metz, September 7, 1953	0 ± 0.05
Seine River, Nogent, September 8, 1953	0 ± 0.09
Danube River, Ulm, September 12, 1953	0 ± 0.07

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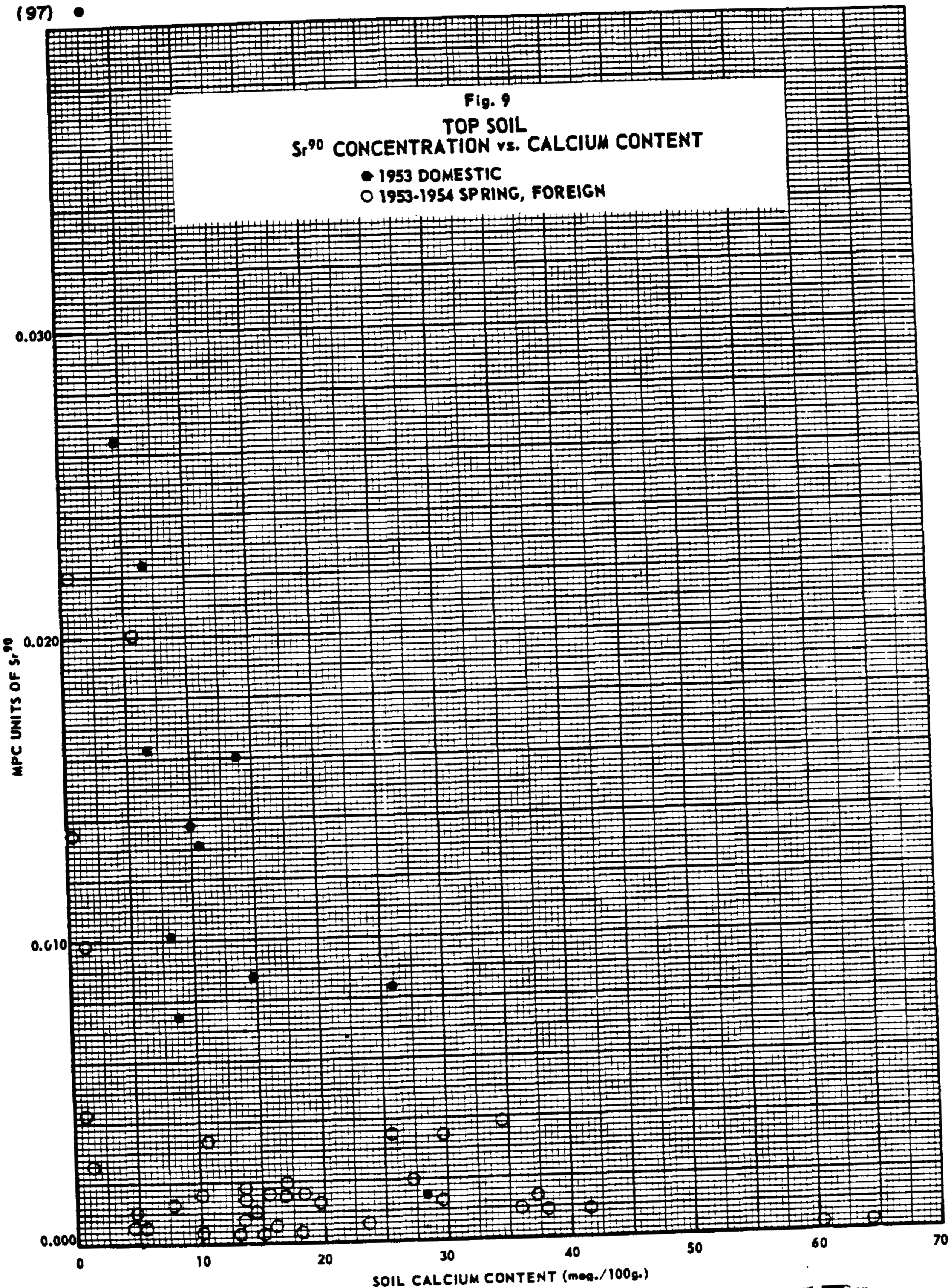

Fig. 9
TOP SOIL
Sr^{90} CONCENTRATION vs. CALCIUM CONTENT

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TABLE 9

GUMMED PAPER COLLECTION EFFICIENCY
Relative to 12-Gallon Pot (18" vertical wall, 12" diameter; cylindrical)

Month	Gummed Paper ($dpm/ft^2/mo$)	Pot ($dpm/ft^2/mo$)	Efficiency (%)	Reference
1954				
March	11.6	14	84	17
April	15.2	31	49	"
May	21.6	34	63	"
June	10.7	9.2	116	"
July	17.6	25	70	"
August	13.5	7.7	176	"
September	20.7	92	22	"
October	3.1	11	29	"
November	5.7	32	18	"
1955				
January	9.0	9.9	92	18
February	29.8	50.6	58	19
March	210	150	140	"
April	44.9	79.5	57	20
May	18.6	56.4	33	21
June	12.4	51.7	24	"
			69 ± 9%*	

*Will use figure of 63% for consistency. Mr. Merril Eisenbud (NYOO) recommends this on the basis of more data and a better statistical treatment.

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mailed to New York Operations Office in an ordinary envelope. Samples thus can be collected cheaply, easily and quickly from any populated area anywhere the postal service reaches. Most of the data so obtained have dealt with total fallout rather than with Sr^{90} specifically, but many analyses for Sr^{90} have been made since Operation Castle. These are presented later.

The main question about the gummed paper technique is its overall efficiency of collection. In order to determine this the HASL has conducted an extensive series of comparisons of the amounts of fallout by gummed paper and a 12-gallon pot with 18" vertical cylindrical wall placed immediately beside the paper. Some of the data thus obtained are given in Table 9. From them we deduce a collection efficiency of 69% ± 9% (but we use 63% since Mr. Eisenbud recommends this on the basis of more data and a better statistical treatment).

The data thus obtained for the Post-Castle Sr^{90} fallout rate in the United States and South America are given in Table 10. These are combined with those for other areas to give the world Sr^{90} fallout rates for September, October, November and December of 1954 and presented in Table 11 and Figure 10.

From these data we obtained these extremely important conclusions:

1. A Sr^{90} fallout probably derived from megaton weapons and nearly uniform over the world, except for local effects due to rainfall variations and to fallout from submegaton weapons, seems clearly

TABLE 10

POST-CASTLE FALLOUT IN U.S. FROM GUMMED PAPERS

Taken at 63% Efficiency (cf. Table 9)

		Sr^{90} Fallout Rate ($mc/mi^2/yr$)	Reference
Sept. 1954	Eastern U. S. (10 Stations)	2.5 ± .2	19
Oct. 1954	Eastern U. S. (10 Stations)	2.0 ± .4	"
Nov. 1954	Eastern U. S. (10 Stations)	2.0 ± .4	"
Dec. 1954	Eastern U. S. (10 Stations)	1.4 ± .2	18
Jan. 1955	Eastern U. S. (9 Stations)	1.3 ± .2	"
Sept. 1954	Western U. S. (20 Stations)	0.9 ± .2	20
Sept. 1954	U. S. (38 Stations)	0.92 ± .2	22
Oct. 1954	U. S. (38 Stations)	0.79 ± .2	"
Nov. 1954	U. S. (38 Stations)	0.95 ± .2	"
Dec. 1954	U. S. (37 Stations)	0.71 ± .2	21
Sept. 1954	South America (12 Stations)	2.1 ± .2	20
Oct. 1954	South America (12 Stations)	1.6 ± .2	"
Nov. 1954	South America (12 Stations)	2.4 ± .2	"

TABLE 11

WORLD-WIDE Sr^{90} FALLOUT RATE FROM GUMMED PAPERS[21],[42] ($mc/mi^2/yr$)
(Taken at 63% Efficiency, cf. Table 9)

Area	% Total Earth's Area	Number of Stations (Sept.)	Sept. 1954 Rate ($mc/mi^2/yr$)	Oct. 1954 Rate	Nov. 1954 Rate	Dec. 1954 Rate	Average Rate
Arctic	6.5	5	1.2 ± .4	3.0 ± .4	1.4 ± .4	.9 ± .4	1.6 ± .2
North Temperate	10.9	14	1.7 ± .24	.68 ± .24	1.4 ± .24	.6 ± .24	1.1 ± .12
Pacific	8.0	2	0 ± .6	.6 ± .6	1.9 ± .6	1.2 ± .6	0.9 ± .3
U. S.	1.5	39	1.3 ± 1.4	.9 ± .14	1.4 ± .14	.9 ± .14	1.1 ± .07
North Tropic	18.5	8	.7 ± .3	1.5 ± .3	.7 ± .3	.4 ± .3	0.8 ± .16
South Tropic	25.5	9	3.2 ± .3	2.4 ± .3	2.5 ± .3	.6 ± .3	2.1 ± .15
				Average (Area Weighted)			1.5 ± .1

	Jan. 1955	Feb. 1955	Mar. 1955	Apr. 1955	May 1955	June 1955	July 1955	Aug. 1955	Average Rate
Arctic	0.32	1.2	0.52	0.62	2.0	1.5	1.6	0.82	1.07
North Temperate	1.0	0.55	1.1	1.1	2.9	1.9	2.5	1.4	1.57
Pacific (21 Stations)	0.53	0.58	2.2	1.1	1.6	1.3	1.2	1.0	1.19
U.S.	0.86	0.86	1.4	2.3	4.0	2.8	2.9	1.4	2.07
North Tropic	0.71	0.70	1.2	0.78	1.5	0.80	0.87	0.50	0.88
South Tropic	1.5	1.3	0.83	0.40	1.0	1.5	0.60	0.72	0.98
South Temperate (4 Stations)	1.1	0.46	0.9	0.40	0.38	1.9	1.1	1.4	0.74
					Average (Area Weighted, Except U. S. and North Temperate Omitted because of Teapot)				0.95 ± 0.1

4/8 [illegible]

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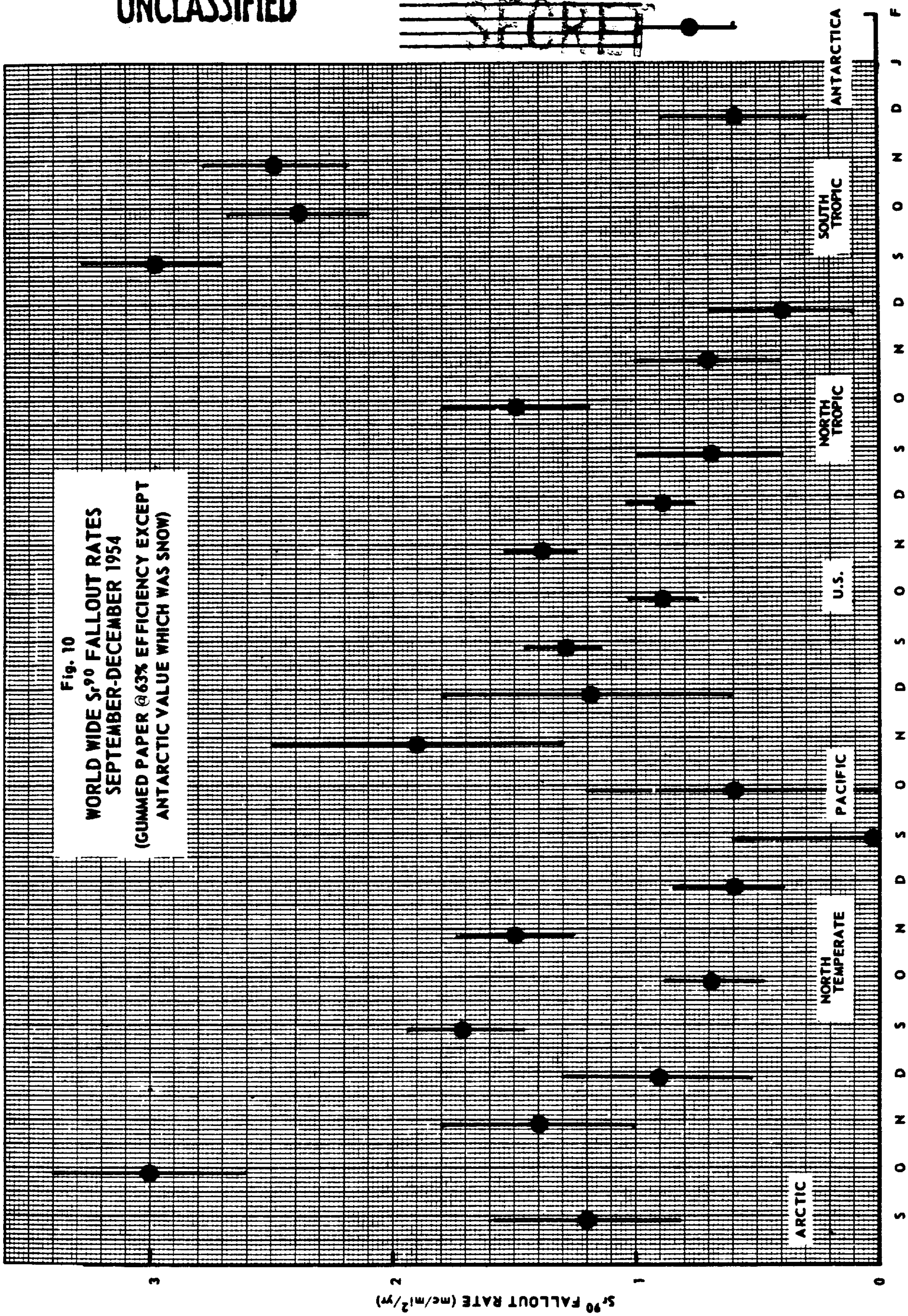

Fig. 10
WORLD WIDE Sr^{90} FALLOUT RATES
SEPTEMBER-DECEMBER 1954
(GUMMED PAPER @63% EFFICIENCY EXCEPT ANTARCTIC VALUE WHICH WAS SNOW)

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established. The fallout from the kiloton weapons lasts only a few weeks at most, since they involve only tropospheric storage, but wide-spread fallout is found to occur at least 1.7 years after a megaton test series.

2. This world-wide Sr^{90} fallout rate in the fall of 1954 and spring and summer of 1955 was 1.2 mc/mi^2/yr (see Table 11).

3. The stratosphere storage time is roughly 10 ± 5 years. The total Sr^{90} stored was 11.3 mc/mi^2 in the fall of 1954 (cf. Table 12).

Table 12 gives the estimated total Sr^{90} delivered into the stratosphere as of October 1954. The justification for the figures for the fractional fallout locally from the various shots is given in Tables 13, 14, 15, 16, 17 and 18 and Figs. 11, 12, 13, 14 and 15. It is clear that the uncertainties in our values of the fractional local fallout are nearly unknown, but we can estimate from the general agreement of the results given in Table 13 that they probably are not greater than about one-quarter of the values given. Since Sr^{90}, in contrast to the bulk of the fission products, has a gaseous precursor, Kr^{90}, which lasts for 50 seconds on the average, there is a considerable likelihood of fractionation so the fraction of Sr^{90} falling out locally may well be different than for the general fission product mixture. Evidence for this is to be seen in the [illegible] (data in Table 13. However, the general point is that the main portion of the Sr^{90} was placed in the stratosphere so errors in the local fallout can be large and yet not be overwhelmingly serious in our considerations.

TABLE 12

SUMMARY OF CASTLE STRATOSPHERIC DELIVERY AND STORAGE AS OF OCTOBER 1, 1954

(Best Summary of data is "Fallout Symposium," January, 1955; AFSWP-895[27])

Fission Yield		Local Fallout	Sr^{90} (mc/mi^2)
	Island	(cf. Table 13 and Fig. 11)	0.6
	Barge		3.3
	"		2.6
	"	(cf. Table 13 and Figs. 12 and 13)	3.8
	"	(cf. Table 13 and Figs. 14 and 15)	0.5
		Total	10.8
		Pre-Castle (Mike, King and Russian Shots) at Castle time	0.45
		Total Post-Castle Stratospheric Sr^{90} at Castle time	11.3
		Corrected for Decay (Half-life 27 years) and Fallout (10 year storage time)	10 ± 5

TABLE 13

CASTLE LOCAL FALLOUT

Shot			
Total Yield* (MT)	15	13	1.7
Fission Yield* (MT)			
Condition	Coral Island	Barge	Barge
Fallout	(Fig. 11)	Sr^{90} (Table 16 and Figs. 12 and 13)	(Table 16 and Figs. 14 and 15)

* From WT - 940

**Final report for Scripps-NRDL Project 2.7 gives local fallout for respectively, according to Dr. E. A. Martell.

TABLE 14

FALLOUT CALCULATION FOR SHOT
(NYO-4618, p.17, as corrected by Memo from Graveson to Levine, 8/11/55.)

Region (cf. Fig. 12	Average Surface Intensity at 48 hours (mr/hr)	$\mu c/cm^2$	Area (mi^2)	Megacuries
0 - 10	4.9	42	1223	1720
10 - 20	14.7	122	496	2020
20 - 30	24.1	198	196	1310
> 30	30	247	40	330
			1955	5400

or observed
local fallout on
total fission
products vs.
from observed
Sr^{90} (cf. Table 16)

TABLE 15

FALLOUT CALCULATIONS FOR
(NYO-4618, p. 21)

Region (cf. Fig. 15)	Average Surface Intensity at 48 hours (mr/hr)	Beta mc/cm^2	Area (mi^2)	Beta Megacuries
Northeast Area				
0 - 1	0.5	6	2130	425
1 - 2	1.5	14	936	435
2 - 3	2.5	22	414	308
3 - 4	3.5	30	83	84
4 - 5	4.5	38	14	19
> 5	5	42	3	4
			3580	1275
West Area				
0 - 2	1.0	10	524	175
2 - 4	3.5	30	184	186
4 - 6	5.3	45	87	130
> 6	6.5	55	35	42
			830	533
				1808 Total

or [illegible] local fallout

TABLE 16

LOCAL Sr^{90} FALLOUT FROM CASTLE SHOTS

(Calculation and Data on Sr^{90} by Dr. E. A. Martell.5/,7/)

CL #	Castle Event	Station(2)	Depth (meters)	Time of Collec. (hours)	Total Fission Prod. Activity(3) (arbitrary)	Sr^{90} Activity (dpm/liter)	Total Sr^{90}(5) (dpm/sq.meter)
473	[redacted]	#1	0	+34	3600	165 ± 9.7	
474	"	"	42	"	4000	61.0 ± 6.4	5.3×10^6
814P	"	"	73	"	400	9.2 ± 1.0	
815P	"	#3	0	+48	1300	8.98 ± 0.63	
816P	"	"	24	"	1900	21.6 ± 1.7	
817P	"	"	44	"	2000	21.4 ± 1.6	1.8×10^6
818P	"	"	80	"	1600	16.6 ± 1.5	
819P	"	"	115	"	120	1.17 ± 0.37	
650P	"	#6	0	+66	440	23.2 ± 2.5	
651P	"	"	19	"	740	17.5 ± 1.6	1.1×10^6
652P	"	"	33	"	440	9.10 ± 0.61	
653P	"	"	52	"	400	7.65 ± 0.59	
820P	"	#7	0	+82	580	28.9 ± 2.9	
821P	"	"	21	"	740	8.97 ± 0.90	
822P	"	"	39	"	510	8.94 ± 0.89	0.87×10^6
823P	"	"	59	"	640	6.76 ± 0.75	
824P	"	"	100	"	50	2.34 ± 0.57	
475	"	#8	0	+106	4400	323 ± 24	
655P	"	"	21	"	4700	74.1 ± 5.2	7.4×10^6
476	"	"	39	"	8400	102 ± 4	
656P	"	"	63	"	890	30.0 ± 2.1	

TABLE 16 (Continued)

657P	(4)	#26	0	< 30	2387	167 ± 8.4
658P	"	#28	0	"	1974	90.0 ± 4.3
659P	"	#54	0	"	3251	259 ± 17
660P	"	#57	0	"	1475	260 ± 13

Notes:

(1) Tritium content of surface sample at Station #1, CL 473, was 15×10^{-18} T/H.

(2) Station Locations:

Station Number	Position at Time of Collection	Distance Downwind from Zero, Corr. for Drift
1	12°10'N; 166°1.8'E	60 naut. miles
3	12°19.4'N; 166°57.2'E	120 " "
6	12°30'N; 167°35'E	165 " "
7	12°59.6'N; 168°26.6'E	233 " "
8	11°52'N; 165°34'E	60 " "

(3) Total fission product gamma activity data are those of USNRDL (Column 9, Table 4.2 and Column 5, Table 4.3, Reference 35).

(4) The 4 samples are from points of maximum observed activity.

(5) Calculation of local fallout from Sr^{90} data: The Sr^{90} data in the last column, Table 16, were obtained by graphical integration of the Sr^{90} concentration data above the thermocline ($\sim$100 meters). The weighted average of the ratios of dpm Sr^{90}/m^2 to surface water gamma activity was used to estimate the corresponding Sr^{90} activity per square meter for all the surface water samples of Table 4.2, Reference 35. Approximate integration of these data gave a value of 4.1×10^4 curies of Sr^{90} deposited locally. We estimate that per cent of Sr^{90} produced by fell out locally. The estimated error in this result is 25 per cent.

TABLE 17

AIR FILTER DATA, WASHINGTON, D. C.
(Army Chemical Corps Type 5 Paper,
99% efficient down to few tenths microns,
75% efficient down to .01 micron.)

Washington, D. C.	Sr^{90} (dpm/10^6 ft^3)	Equivalent* Fallout (mc/mi^2/yr)
1953		
April 5-8	18.6 ± .7	0.14
October 2-6	41.1 ± 3.0	0.3
October 6-9	30.5 ± 1.1	0.2
October 12-15	70.4 ± 12	0.5
1954		
April 3-5	91.0 ± 7	0.7
April 8-10	6.4 ± .2	0.05
April 10-12	258 ± 6	1.9
April 12-14	65.5 ± 4.6	0.5
April 15-17	11 ± .5	0.08
April 17-19	21 ± .6	0.16
April 29-May 1	32.2 ± 2.6	0.2
May 11-13	31.3 ± 2.2	0.2
May 24-26	216 ± 11	1.6
June 1-3	68.3 ± 4	0.5
July 16-17	73.5 ± 5.2	0.5
July 26-29	48 ± 3.9	0.36
November 1-3	120 ± 7	0.9
December 1-2	103 ± 4	0.8
1955		
January 3-4	281 ± 6	2.1
February 5-6	127 ± 5	0.9
February 10-12	241 ± 10	1.8
February 22-23	202 ± 11	1.5
March 3-4	270 ± 13	2.0
March 7-8	394 ± 20	2.9
March 13-14	267 ± 16	2.0
March 16-17	310 ± 15	2.3
March 22-23	393 ± 20	2.9

---

*134 dpm/10^6 ft^3 = 1 mc/mi^2/yr (cf. text).

(28300 ft^3/ft^2 = 10^6 ft^3/35.5 ft^2)

TABLE 18

STRATOSPHERE STORAGE TIME

Pre-Castle (Mike):

$$\tau = 4 \pm 2 \text{ years}$$

Post-Castle:
U. S. Rains
(cf. Fig. 8)

$$\tau = \frac{10 \pm 5}{2.3 \pm .2} = 4.4 \pm 2$$

World-Wide Gummed Paper
(cf. Table 13 and Fig. 10)

$$\tau = \frac{10 \pm 5}{1.2 \pm 0.1} = 8.4 \pm 4 \text{ years}$$

Air Filters
(cf. Table 17 and Fig. 16)

$$\tau = \frac{10 \pm 5}{.70 \pm 0.2} = 14 \pm 7 \text{ years}$$

General Average 10 ± 5 years.

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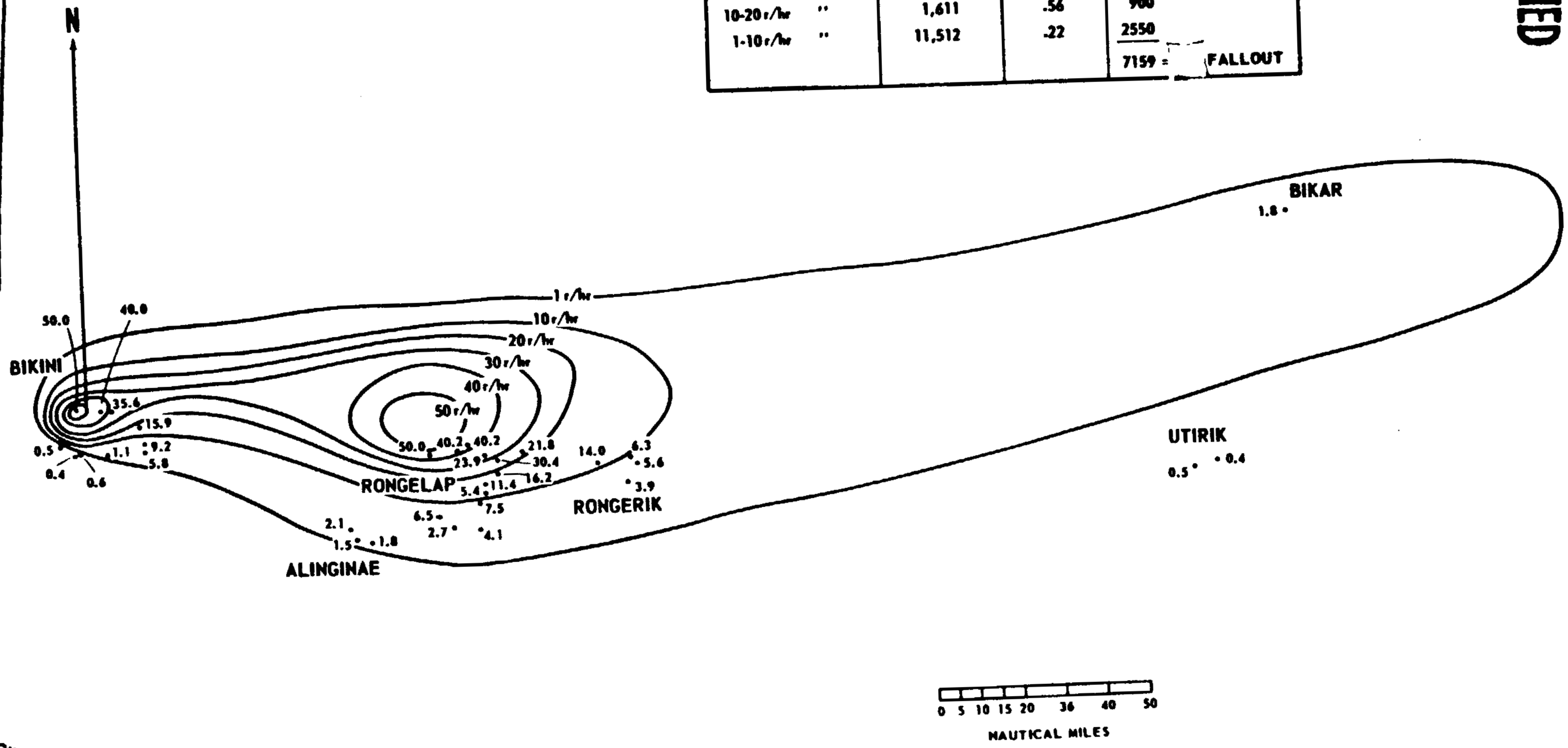
CASTLE BRAVO FALLOUT

24 HOUR DOSE RATES

Fig. 11

FALLOUT 27/ 43/ 44/

CONTOURS	AREA $(NM)^2$	KT/$(NM)^2$	KT
>50 r/hr at 24 hrs.	211	2.44	512
40-50 r/hr "	435	1.95	840
30-40 r/hr "	947	1.46	1390
20-30 r/hr "	746	1.28	957
10-20 r/hr "	1,611	.56	900
1-10 r/hr "	11,512	.22	2550
			7159 = FALLOUT



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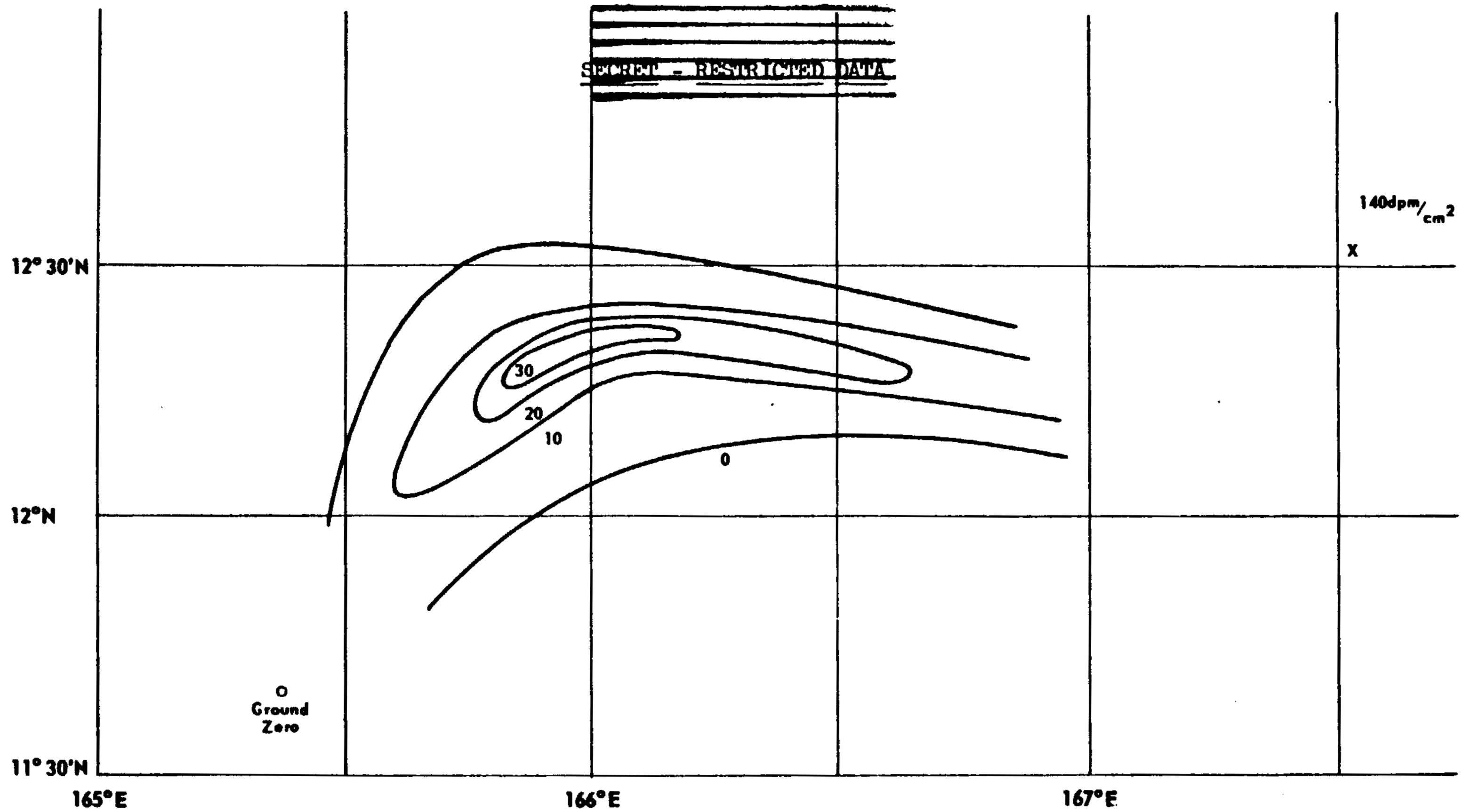

FIG. 12

FALLOUT (Mr/Hr AT 48 HRS ;

WITH Sr^{90} AS CROSS (TABLE 18))

([24a]NYO 4618, FIG. 14)

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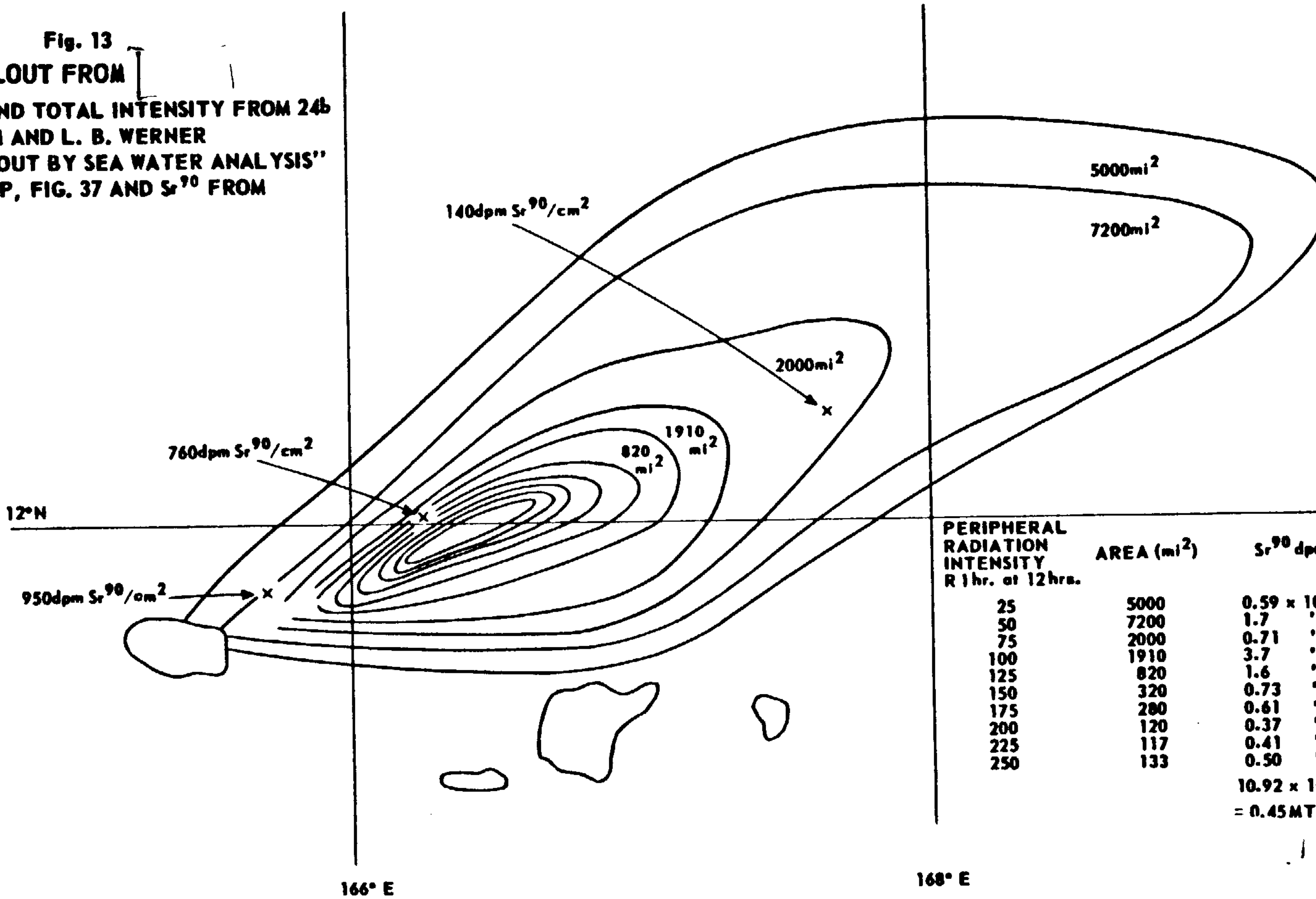
Fig. 13

FALLOUT FROM

(CONTOURS AND TOTAL INTENSITY FROM 24b
T. R. FOLSOM AND L. B. WERNER
"DIST.-FALLOUT BY SEA WATER ANALYSIS"
ITR-915 ASFWP, FIG. 37 AND Sr^{90} FROM
TABLE 18)



PERIPHERAL RADIATION INTENSITY R 1hr. at 12hrs.	AREA (mi^2)	Sr^{90} dpm
25	5000	0.59×10^{16}
50	7200	1.7 "
75	2000	0.71 "
100	1910	3.7 "
125	820	1.6 "
150	320	0.73 "
175	280	0.61 "
200	120	0.37 "
225	117	0.41 "
250	133	0.50 "
		10.92×10^{16}
		= 0.45MT

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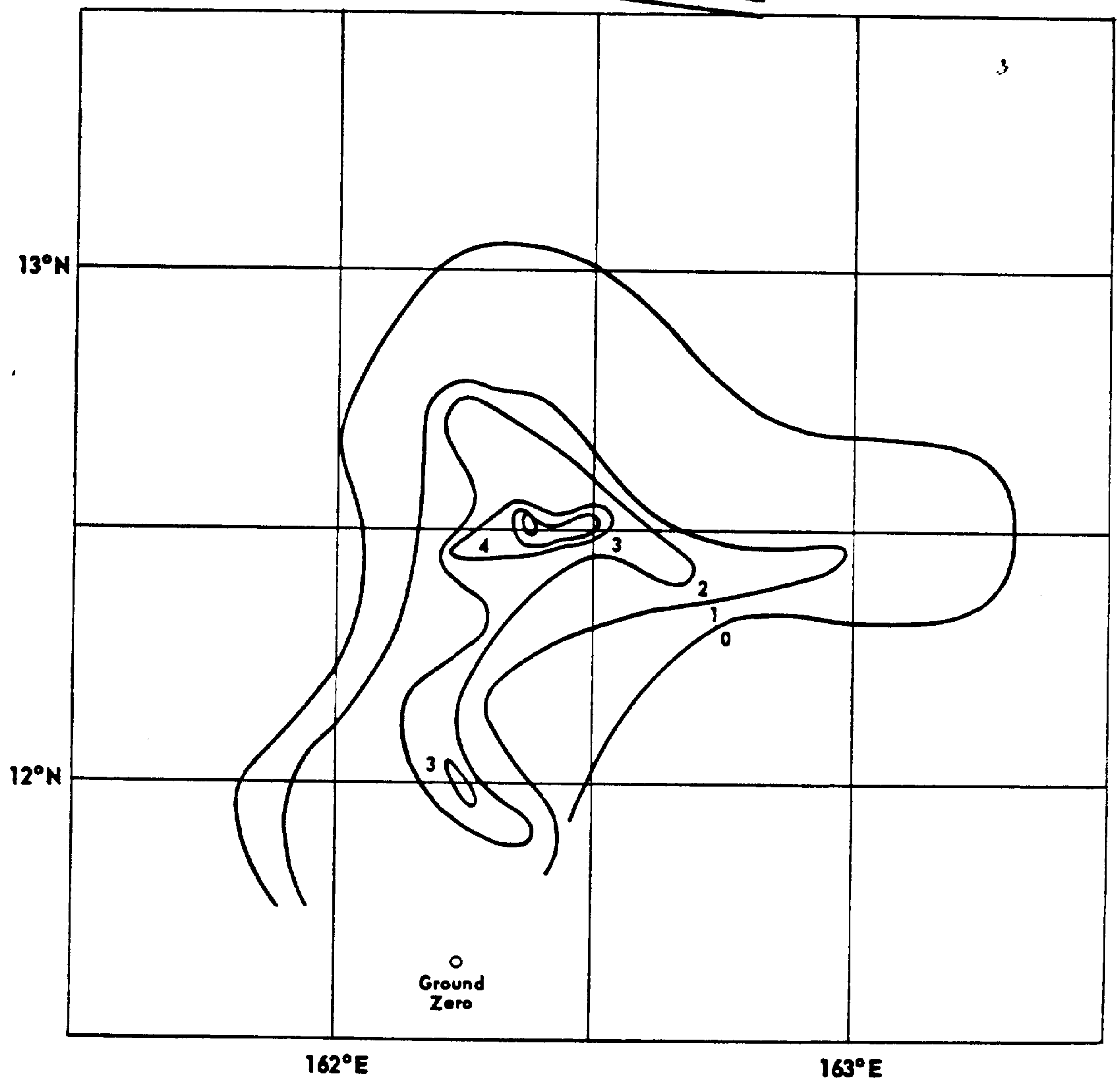

FIG. 14
FALLOUT FROM [redacted] NORTHEASTERN SECTION
(24a NYO 4618, FIG. 15)
(Mr/Hr AT 48 HRS.)

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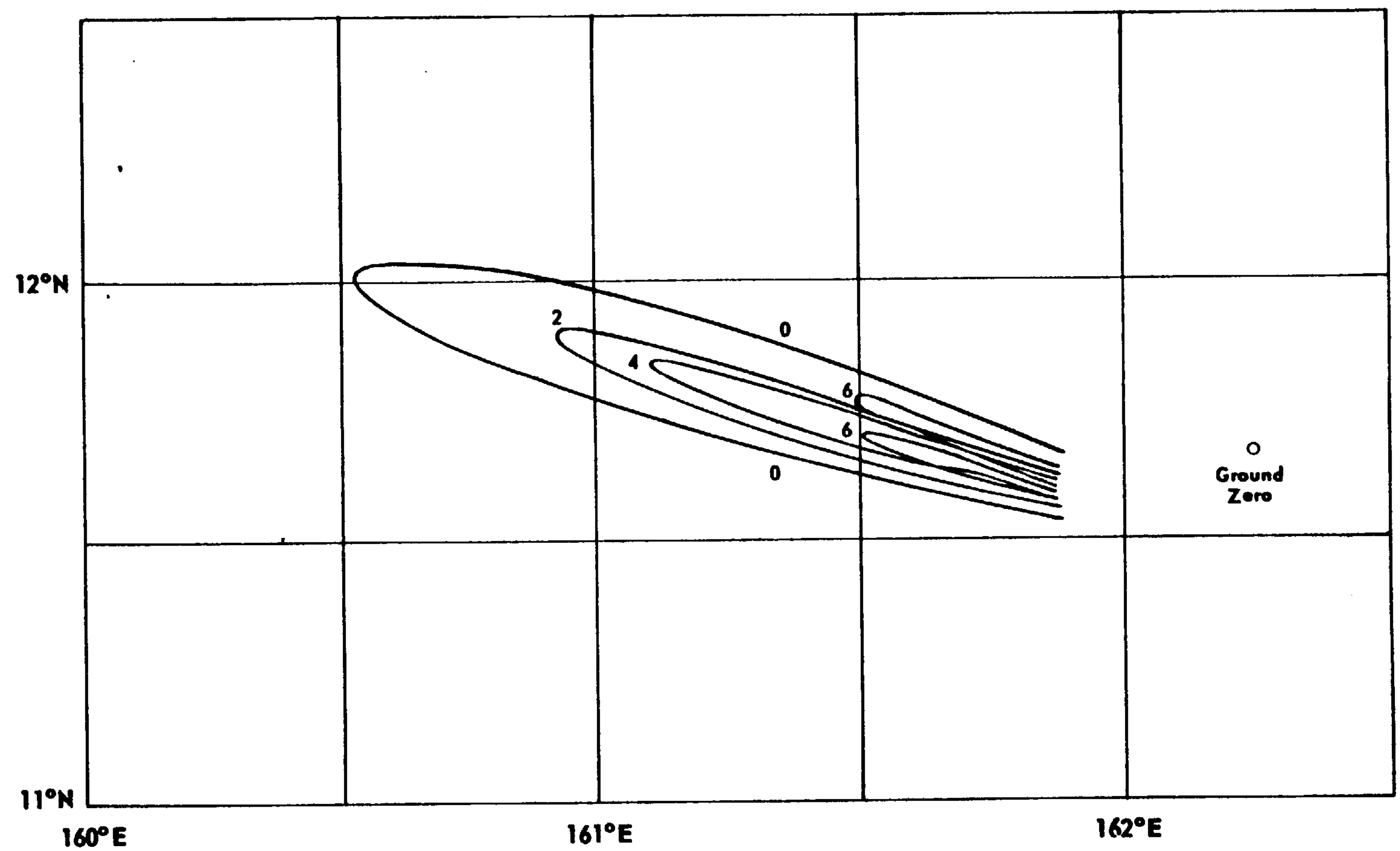

FIG. 15
FALLOUT, WESTERN SECTION
(^{24a}NYO 4618, FIG. 16)
($^{Mr}/_{Hr}$ AT 48 HRS.)

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Additional information available on the Sr^{90} distribution has been obtained by air filters operated at sea level principally by the Naval Research Laboratory and measured in the Chicago Laboratory, at high altitudes by the British[25] who measured mixed fission products, and by Health and Safety Laboratory of NYO[26] who measured Sr^{90}. Surface samples collected at Washington, D. C., by the NRL and measured at Chicago[2], [5], [6], [7], [8] are given in Table 17 and Fig. 16. In order to correlate these data with the fallout rate, we recall that as remarked previously, any rain of 0.1 inch or more probably will thoroughly wash down the fallout in the air below the layer at which the rain originates. Examination of the weather data for the Washington, D. C., area in the period when the samples were taken shows that the average interval between rains was 6 $\pm$ 3 days. Therefore, the Sr^{90} content of surface air should correspond to fallout for this time on the average, and we would expect a fallout rate R($mc/mi^2/yr$) to correspond to a surface air content of $R \times \frac{6}{365} \times 79 \times 41 \times 2.5$ $dpm/10^6\ ft^3$, since 79 dpm/ft^2 is equivalent to 1 mc/mi^2 and there are 41 ft^2 per $10^6\ ft^3$ below the tropopause on the average at Washington, D. C., and 2.5 is the average ratio of height of tropopause to rain bearing layers. The resulting rate of 0.70 $\pm$ 0.2 $mc/mi^2/yr$ is rather definitely low compared to the rain result of 2.3 $\pm$ 0.2 $mc/mi^2/yr$ for Chicago (Fig. 8) and of 1.5 $\pm$ 0.1 $mc/mi^2/yr$ from gummed papers. (Fig. 10 and Table 11.) The uncertainty in the factor of 2.5 for the ratio of rain bearing layer height is probably the principal one in the

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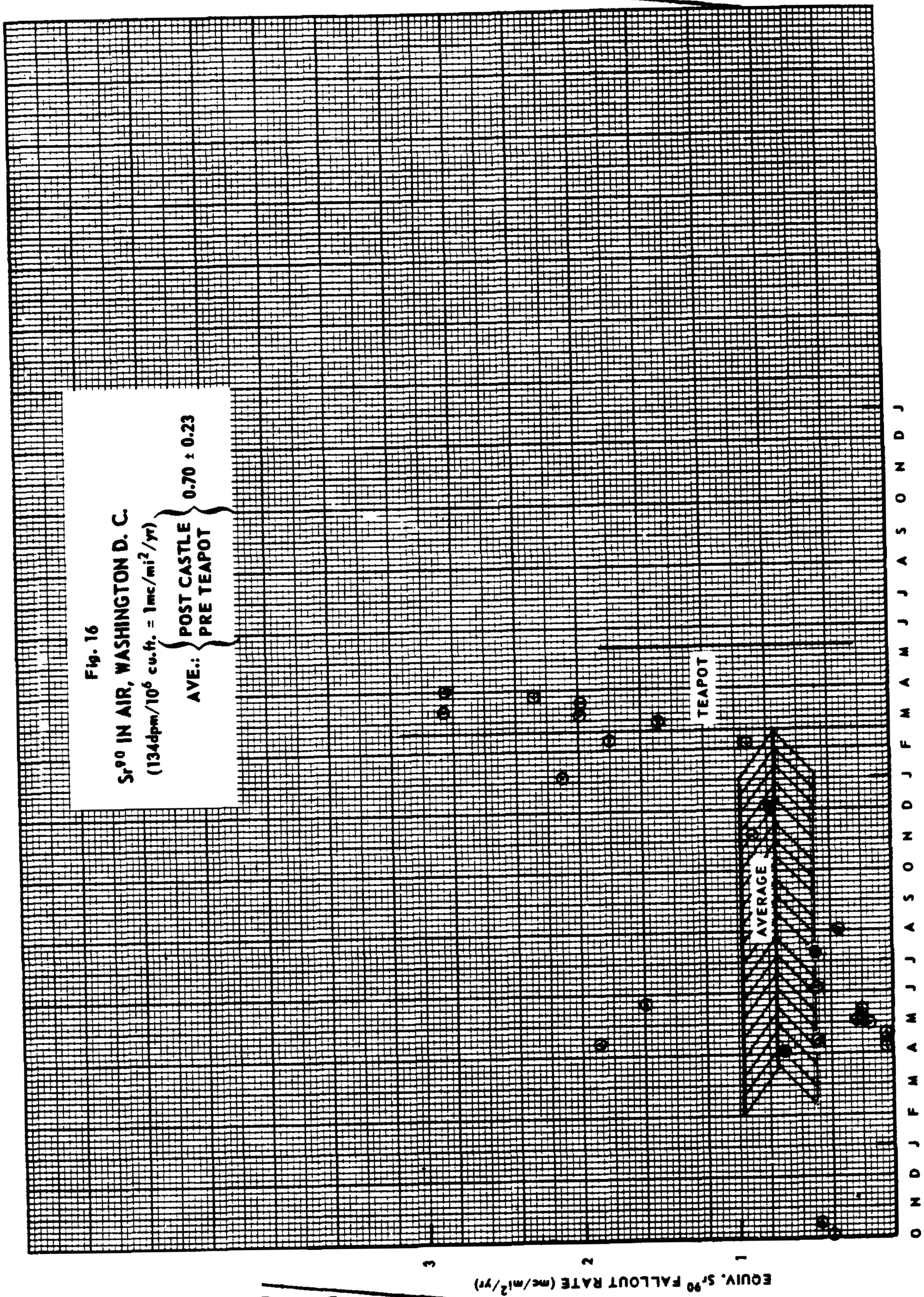

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calculation of the fallout rate from air filter data, though it may be that the perfect vertical mixing of the lower 40% of the troposphere implicit in the calculation is an incorrect assumption, in that air right at the surface is cleaned to a considerable extent by surface contact with vegetation and water and soil and therefore has less fallout than the average for the lower troposphere.

Table 18 summarizes the four calculations of the stratospheric residence time, τ. We accept as the general result 10 $\pm$ 5 years.

The high altitude data show a definite rise above the tropopause. This is strong confirmation for the stratospheric storage and dissemination mechanism. Fig. 17 is taken from a British report[25]. It shows the general fission product content vs. altitude with the sharp rise at the tropopause expected for the stratospheric reservoir.

II. DISCUSSION

A. Predicted Sr^{90} Fallout.

The stratosphere reservoir of Sr^{90} immediately after Operation Castle had been completed was 11.3 mc/mi^2, or the equivalent of 22 MT of fission energy as shown in Table 12. The fallout rate of Sr^{90} corresponds to an average storage time of 10 years and essentially uniform world-wide dissemination — as shown in the preceding section but particularly in Table 18. The radioactive half-life of Sr^{90} is 28 years corresponding to an average life of 40 years. Therefore, the Sr^{90} fallout rate from tests up to and through the Castle Series should be given by

$$R = \frac{1}{10}\, 11.3 e^{-t\left(\frac{1}{10} + \frac{1}{40}\right)} \text{ mc/mi}^2\text{/yr} \quad (1)$$

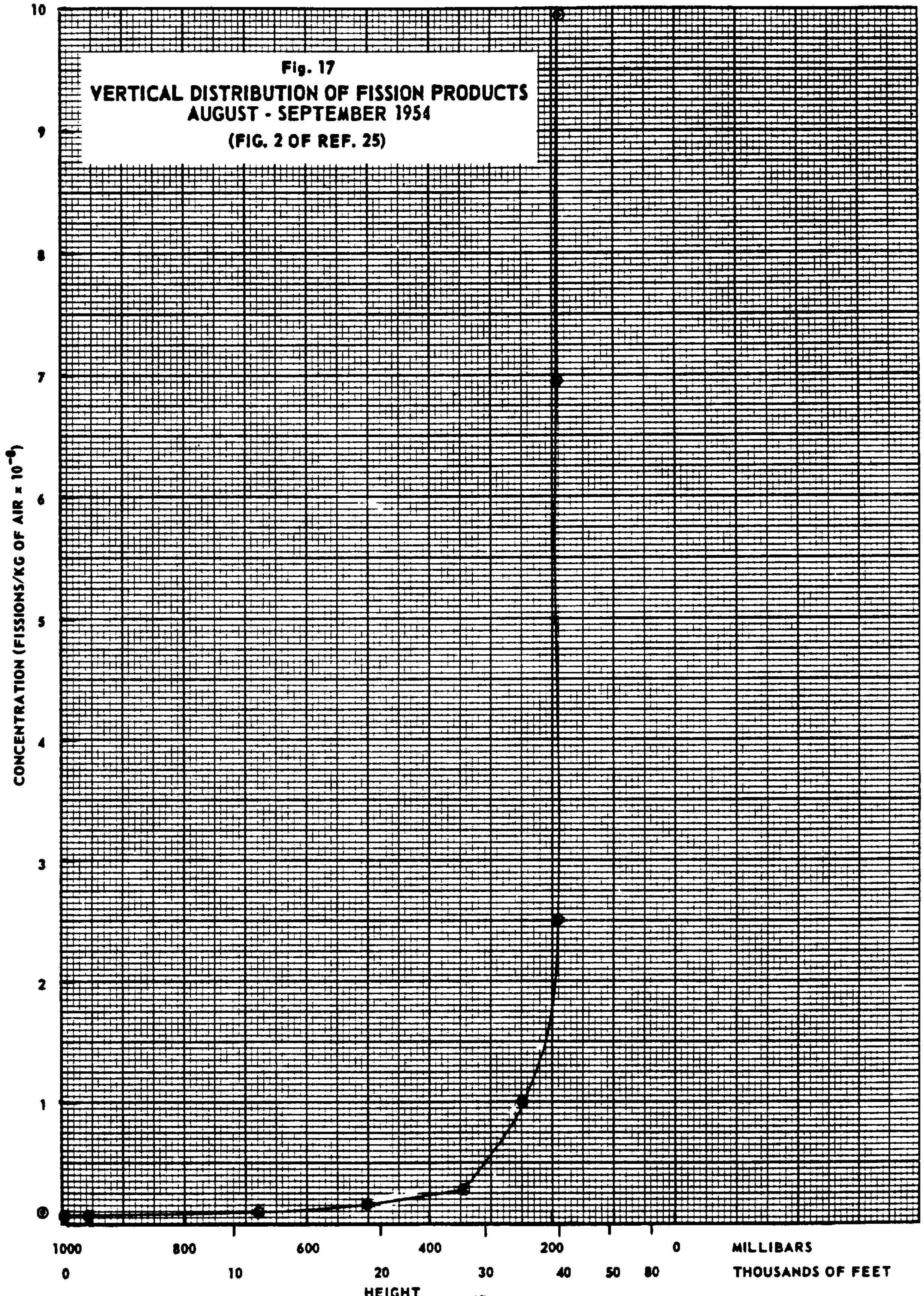

Fig. 17
VERTICAL DISTRIBUTION OF FISSION PRODUCTS
AUGUST - SEPTEMBER 1954
(FIG. 2 OF REF. 25)
CONCENTRATION (FISSIONS/KG OF AIR x 10⁻⁸)
10
9
8
7
6
5
4
3
2
1
0
1000
800
600
400
200
0
MILLIBARS
0
10
20
30
40
50
80
THOUSANDS OF FEET
HEIGHT

67 108

where t is the time elapsed, in years, since May 1954. This relation is given in Fig. 18. From it we can predict the tropospheric air content to be

$$A = R \frac{T}{365} \times 2.5 \times 79 \times 41 \quad \text{dpm}/10^6\text{ft}^3, \qquad (2)$$

where the period of T days elapses between the rains washing out the air mass concerned. Taking T to be 6 days on the average the surface air should contain 134 R dpm per 10^6 ft^3 in the middle latitudes.

The rainfall content will be 4R dpm/gal for regions with an annual rainfall of 31.5". The values for other annual precipitations are to be derived by inverse proportion, e.g. in Antarctica where the annual precipitation is about 1/4 of 31.5", the Sr^{90} content of snow should be given by 16R or

$$A^1 = 16 \times 1.13e^{-t} \frac{1}{10} + \frac{1}{40} \quad \text{dpm/gal.} \qquad (3)$$

In this connection, it is very important to note that regions of frequent rainfall very probably will receive more Sr^{90} fallout than will more arid regions.

Of course, some fallout will be deposited by the surface winds blowing over the leaves of trees and grass. For example, the Naval Research Laboratory[6] has mounted an uncharged platinum screen vertically and held normal to the surface winds by a large vane. The deposition is by impact. Two weeks' total collections were made and these gave up to 20 times as much as for gummed papers of the same area exposed for the same time in the same place. The screen was 80 mesh and probably passed about 0.5×10^6 ft^3 in the

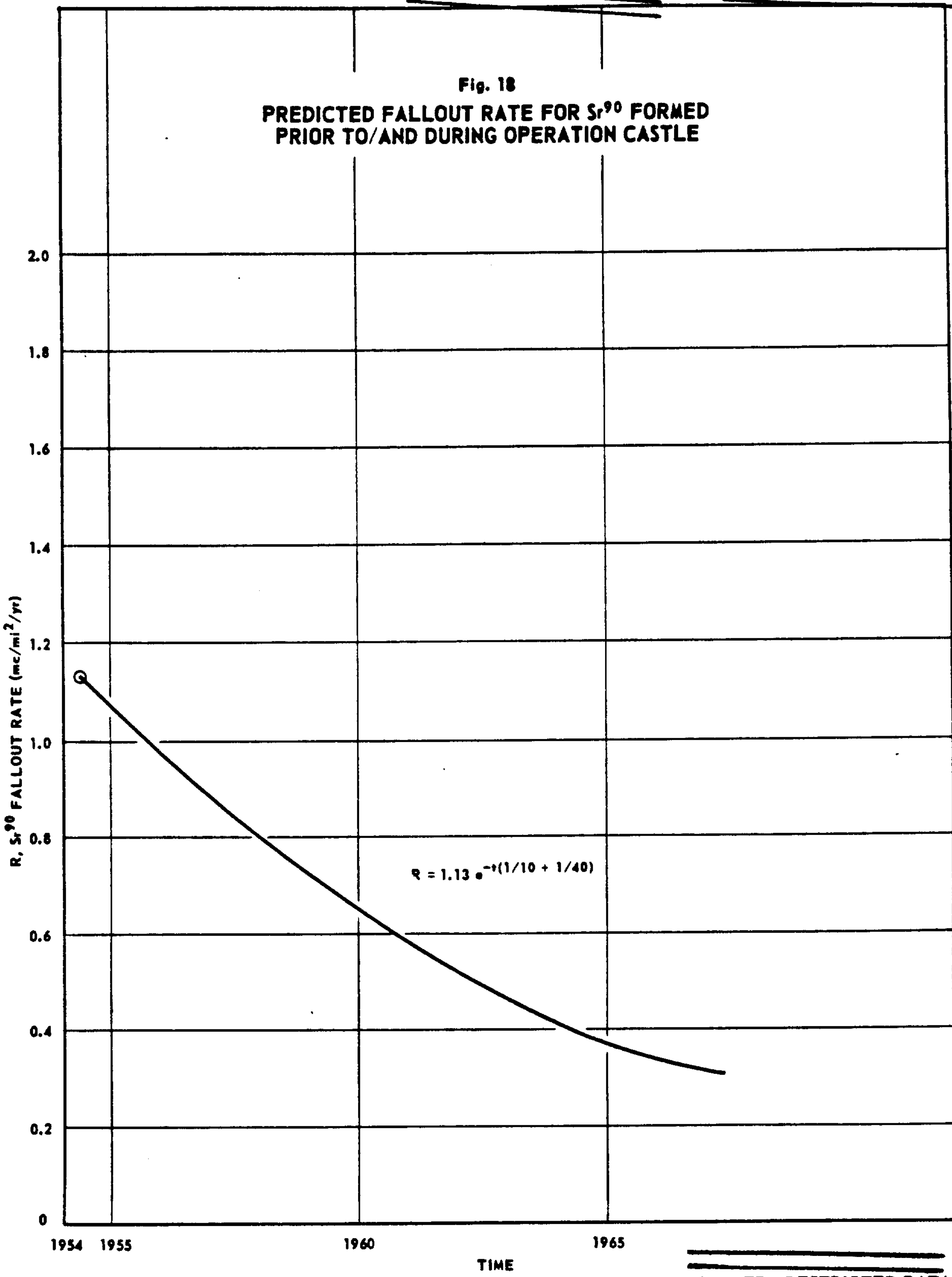

Fig. 18

PREDICTED FALLOUT RATE FOR Sr^{90} FORMED PRIOR TO/AND DURING OPERATION CASTLE

two weeks' exposure. From this it is clear that surface contact of fallout-laden tropospheric air must result in deposition. Further evidence for this is seen in Table 1 where there is seen to be essentially no correlation between the Sr^{90} contents of soils and the crops of alfalfa grown on them. There obviously must have been very considerable direct deposition on the surface of the plants. Also, the relatively low values for the Sr^{90} content of surface air found by the Naval Research Laboratory (Table 17) calculated with respect to the observed rain content may very well be due to surface deposition by direct contact on tree leaves and grass.

The soil content will be the total of all fallout radioactivity less any natural weathering processes which serve to remove the fallout Sr^{90} from the chemically available form in which plants can assimilate it. Neglecting this latter effect, though as we shall see there is reason to believe such effects are operative in an important way, and taking the average for the exchangeable Ca content of soils over the world, cf. Tables 2 and 3, which is 8 g/ft^2/in, we calculate that the top 2.5" of soil which in general holds nearly all of the Sr^{90} (Tables 2 and 3) has some 20 g of exchangeable Ca. Therefore, we predict that in the absence of curative weathering effects acting to remove Sr^{90} from contact with the biosphere, the average Sr^{90} concentration of exchangeable

Ca should be

$$S = 79.2\ \frac{\left(P + \int_0^t R\ dt\right)}{2.2 \times 20}\quad \text{Sunshine Units, where} \qquad (4)$$

P is the Pre-Castle deposition of 0.8 mc/mi^2 in the middle latitudes and 0.2 mc/mi^2 world-wide. Thus in the middle latitudes the Sr^{90} concentration of exchangeable soil Ca should be given by

$$S(\text{Sunshine Units}) = 79.2\ \frac{\left(0.8 + 1.13 \int_0^t e^{-t\ \frac{1}{10}}\ dt\right)}{2.2 \times 20}\ e^{-\frac{t}{40}} \qquad (5)$$

or

$$S(\text{Sunshine Units}) = \left[1.5 + 20.3(1 - e^{-\frac{t}{10}})\ e^{-\frac{t}{40}}\right] \qquad (6)$$

This result is presented graphically in Fig. 19. The maximum Castle Sr^{90} soil activity will be expected in about 1970. The present average should be about 5 Sunshine Units for soil with 20 g exchangeable Ca/ft^2. Those soils of low Ca content can, of course, have a much higher Sr^{90} content for unit amount of exchangeable Ca. Consider, for example, certain areas in Wales near Cardigan (cf. Table 3, Sample No. 54417), where the available Ca amounted to only 0.4 g/ft^2 and the specific Sr^{90} activity was found to be 97 S.U. For this area our analysis would predict forty-fold higher than given in Fig. 19 — a maximum of about 610 in 1970 and 220 Sunshine Units at the present time. This, of course, should be reflected in higher contents for the bones of grazing animals. In the spring of 1955 two lambs from this general area[6] (Cwmystwyth in Wales and Suffolk, England) analyzed 60.1 $\pm$ 1.2 and 31.4 $\pm$ 0.6 Sunshine Units.

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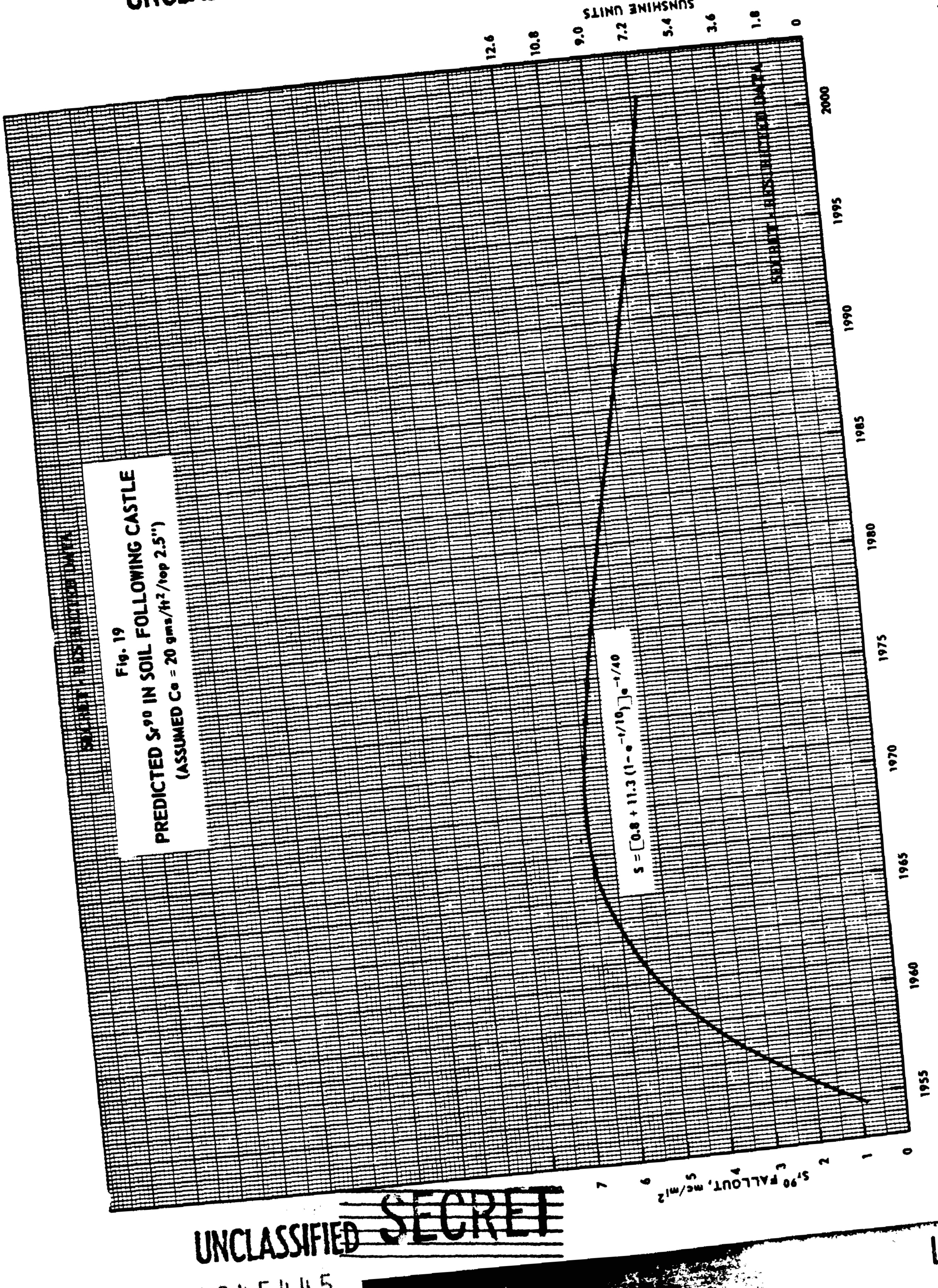

Fig. 19

PREDICTED Sr^{90} IN SOIL FOLLOWING CASTLE

(ASSUMED Ca = 20 gms/ft²/top 2.5")

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The weathering processes which may operate to fix the fallout Sr^{90} and make it unavailable to the biosphere such as the fixation in massive Ca deposits are worth consideration. Only further investigation will reveal how important such processes are. The present Project Sunshine sampling program includes repeated sampling of given regions. The data so obtained should disclose any such trends. Some data already in hand seem to indicate such effects, but further confirmation is necessary.

In addition, palliative measures may prove effective. For example, Nervik, Kalkstein, and Libby[41] have shown that milk can be purified for radiostrontium by a treatment which may well prove to be quite practical and inexpensive.

B. Biosphere Content of Sr^{90}.

It seems clear that there will be discriminatory barriers of some magnitude operating at each of the stages of transfer from the soil into the biosphere. Taking these stages in general to be:

1. Soil $\longrightarrow$ Plants
2. Plants $\longrightarrow$ Animals
3. Animals (milk) $\longrightarrow$ Humans

we consider the three corresponding barriers.

1. Soil to Plant Transfers.

In Table 19 the Sr^{90} contents of plants are compared with those for the soils on which they grew at a variety of localities just before Operation Castle. It seems clear that on the average plants have about twice the specific Sr^{90} content relative to Ca

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TABLE 19

PRE-CASTLE PLANT Sr^{90} CONTENTS (SUNSHINE UNITS)

Location	Plant	Date	Reference	Plant Content	Content of Soil Which Grew Plant
U. S.	Alfalfa	(Average of Table 1)		8.9	4.7 ± 0.4
Turkey	Alfalfa	10-53	(2)	2.16 ± 0.18	1.2 ± 0.1
Cuba	Tobacco	4-54	(2)	1.7 ± 0.2	(1.6)*
New Zealand	Forage	11-53	(5)	1.17 ± 0.28	≤ 0.21
" "	Forage	1-54	(5)	0.84 ± 0.10	≤ 0.18
Chile	Forage	11-53	(6)	0.84 ± 0.02	≤ 0.33

*Calculated from Average Pre-Castle Deposition (Fig. 4a) for Latitude of Cuba and Assumed Average Ca content of 20 g/ft^2 in top 2.5".

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(Sunshine Units) that the supporting soils do. It seems very likely that this is due in part to fallout occurring directly on the external plant surfaces. This is further borne out by the lack of detailed correlation in Table 1 between soil and alfalfa results for eleven Middlewestern U. S. farms. From this result we may calculate that about half of the total Sr^{90} content of alfalfa is due to direct fallout, while for general forage it is probably an even higher percentage. This comparison is not quite accurate, because although almost all of the Sr^{90} is contained in the top 2.5" of soil, the Ca, on the other hand, is available to the entire depth of the root system. It is also recognized that the vertical distribution of the Ca may be non-uniform. There is no reason to expect preferential assimilation of Sr from the soil relative to Ca so the only other explanation for the data in Table 19 is direct fall-out. As remarked in Section I in the paragraphs on rain and air filter data, there are two mechanisms for direct fallout of the ultra finely divided particulate matter carrying the Sr^{90} in the stratospheric reservoir -- rainout and contact deposition after the fallout has entered the troposphere. Rainout appears to be the principal mechanism though it has been demonstrated by the Naval Research Laboratory 28/, 29/, 30/ as mentioned earlier that an 80 mesh screen mounted vertically to prevailing surface winds can gather more fallout than falls out directly on the average by all mechanisms. It is not clear, however, to what degree foliage acts

in this way, but the probability seems high that the effect is relatively minor and that rainout followed by drying of raindrops is the main way in which the foliage surfaces gather fallout.

On this basis we conclude that fallout in arid regions should be appreciably lower than in areas with normal rainfall. This effect seems to be borne out by the data available now, though more definitive experiments are needed. It probably follows also that regions subject to seasonal rainfall rather than relatively uniform precipitation all year should show less fallout for the same total annual rainfall. Also, regions subject to frequent morning fogs may be particularly high in total fallout. The Sr^{90} probably will enter the troposphere at relatively uniform rates but the chance of precipitation will depend strongly on the local weather.

Of course, rainfall is necessary to plant growth so plants are certain to gather some fallout. However, for regions of low rainfall where irrigation is used — such as the Imperial Valley in California — the fallout content of the crops should be particularly low, for as shown in Table 8 rivers are nearly free of fallout since the soil purifies the runoff water before it reaches the rivers. Similarly, reservoirs and lakes will be low relative to rain because of dilution and the importance of runoff water from surrounding water sheds in replacing evaporative and withdrawal losses. It is also well to note that ordinary water purification processes are effective in removing an appreciable fraction of the radiostrontium.

The by-passing of soil entirely, which occurs in the direct fallout on plant surfaces, of course, means that the retarding effects of high Ca contents in soil are inoperative and cattle grazing on such foliage may show little correlation in the Sr^{90} contents with the soil Sr^{90} activity for this reason. This appears to be true in the U. S. Midwest from the data in Table 1.

It is clear, however, that washing may reduce the level of fallout externally carried by plants, though direct leaf absorption will be expected to occur rather rapidly for water soluble fallout. For the first of the megaton weapons fired in the Pacific, the Mike and shots, the bulk of the fallout resides on particles of CaO or $Ca(OH)_2$ or mixtures of CaO, $Ca(OH)_2$, $CaCO_3$ made by the great heat of the fireball acting on the coral of the islands and sea floor in the firing areas.[27] In the remaining shots fired on barges it resides largely on NaCl particles. This material, therefore, should be quite water soluble and should be rapidly absorbed into the leaves. Washing, therefore, probably will not be particularly effective for the world-wide fallout, which derives from the Pacific Tests. From weapons fired in the air, the particles probably will consist of less soluble oxides and therefore more likely to wash off of plant surfaces before being absorbed.

Menzel[33] of the U. S. Department of Agriculture grew cowpeas on 42 American soils to which equal amounts of bomb debris had been added. Available Ca ranged from 0.7 to 48 milliequivalents

of Ca per 100 g of soil. The Sr^{90}/Ca ratio of the plants was approximately inversely proportional to the available Ca in the soil over the full range of Ca availability. In another set of experiments on a particular type of soil (Evesboro) to which known amounts of Sr^{90} had been added at two carrier levels, the results listed in Table 20 were found. The distribution factor, k_{Sr}, defined as (Sr/Ca)plant/(Sr/Ca)soil, indicates the discrimination which the plant makes between Sr and Ca uptake. Similar tests were made for Barium.

By combining these data Menzel concluded that the average Sr uptake from American soils was best fitted by a distribution factor of $k_{Sr} = 0.36$. This average probably will apply world-wide about as well.

2. Plant to Animal Transfer.

The Sr^{90} contained in grass and foliage eaten by grazing animals will be retained to an extent dependent on the metabolism of the animal. For example, for a 1 year old steer[31] 30 percent of the Sr^{90} fed orally was retained with essentially no discrimination relative to Ca. There appears to be a higher retention approaching 90% for intravenous injection of young rats.[31] High Ca diets reduce the Sr^{90} uptake for rats and adult rats take up orally about 16% of the ingested Sr^{90} on the same low Ca diet for which young rats took up 73%.[31]

Comar[34] has performed experiments on cows in which the Sr/Ca ratio in feed, blood, and milk was measured under equilibrium

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TABLE 20

PLANT ASSIMILATION OF Sr^{90} FROM SOIL

Crop	(Sr/Ca)Soil (By equivalents)	k_{Sr}	k_{Ba}
Barley	.017	.45	.020
	.0017	.39	.022
Buckwheat	.017	.49	.023
	.0017	.43	.028
Cowpeas	.017	.53	.057
	.0017	.37	.053

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conditions. Typical relative values were 1.0, 0.37 and 0.13, respectively, thus indicating a relative lowering of the Sr^{90} content of the milk relative to the feed. This is borne out by direct observation on the fallout as seen in Table 1 where for the Chicago milk shed the milk averages 1.4 S.U. while the alfalfa fed averaged 8.9 S.U.

3. <u>Milk to Human Transfer</u>.

This ability of the cow to reduce the Sr^{90} in the milk relative to the feed is important as a barrier to human ingestion of this fallout radioactivity. With it in mind we can expect that human Sr^{90} burdens should be 20% or less (for older people) of the plant contents and about equal to the milk and cheese levels if the entire Ca in the body were assimilated at a given Sr^{90} content of the milk.

Since the Sr^{90} content of the whole biosphere is continually rising, about as shown in Fig. 19, the average Sr^{90} content of milk should rise in a similar manner. Therefore, the intake of Sr^{90} by humans is steadily increasing as shown in Figs. 1a, 1b, 1c and 1d. The data in Table 3 and Figs. 1c and 1d show that the milk level at the time of Castle averaged about 1 S.U. peaking in the middle latitudes as did the soil assays (cf. Fig. 4a). This value shows a ratio of 1 to 1.4 for the milk level to the average soil level for the top 2.5 inches of soil with 20 g of contained available Ca/ft^2. This high value probably is due to leaf pick-up of fallout. Taking this as a general result, we predict the world

values for milk and cheese at 70% of the soil values given in Fig. 19 plus any local fallout. This would mean that we would expect average foreign milk and cheese samples to show about 4 S.U. at the present time.

The human bone, of course, is formed during the growing process so the Sr^{90} content of children should be higher in concentration units (Sunshine Units) than for adults. The data[2],[3],[4],[5],[6],[7],[8] verify this prediction; however, for newborn babies there is less than corresponds to the milk for the region, presumably due to the retarding effect of the mother's older Ca pool. Children seem to carry Sr^{90} approximately equal to the average level of the milk during the period of their lives. Adults decrease in Sr^{90} concentration with age as expected. It seems that the adults of the future will have Sr^{90} levels corresponding to the milk levels during their lifetime weighted according to their rate of growth. For example, the years 10 to 18 will be most important for men and 6 to 12 for women. Foreign children born now, according to Fig. 19, should develop about 11 S.U. during their lives. Children born now in the U. S. will develop a somewhat higher level, due to somewhat higher milk levels.

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